STUDY OF DISSIMILAR METAL JOINING BY SOLID STATE WELDING

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ABSTRACT

Dissimilar metal tubular transition joints having diameters of 0.5, 2.0, 4.0 and 8.0-inches were fabricated by diffusion welding from the following alloy combinations:

1. 2219 Aluminum Alloy to AISI Type 321 Stainless Steel
2. 2219 Aluminum Alloy to Ti-5Al-2.5Sn Titanium Alloy
3. AISI Type 321 Stainless Steel to Ti-8Al-1Mo-1V Titanium Alloy

The joints were tested at room temperature and -320°F using thermal shock, random and sinusoidal vibration, pressure cycling, and burst tests for structural reliability as well as to obtain joint design data. Helium leak testing and metallurgical examinations were also used to evaluate joint characteristics.

Discussions are included on tooling and processing techniques applicable to potential production of diffusion welded tubular components. Also, solid state joining results and potential aerospace applications are included for other composite forms.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

INTRODUCTION

The design of components and systems for aerospace vehicles often requires the joining of dissimilar metals to meet the environmental conditions and high performance requirements of the vehicle. This is particularly true in the plumbing lines used for fuel, environmental control and high pressure gas actuating systems. In these applications the tankage materials are normally required to be different from the plumbing line materials because of material requirements in system components such as valves and expansion bellows. Presently large diameter dissimilar metal plumbing lines are joined by mechanical fasteners because of the difficulties in obtaining structurally reliable joints by welding or brazing.

In 1964-65 a development program(1) was conducted to determine methods for producing large diameter 2219 aluminum alloy to AISI type 321 stainless steel tubular transition joints. The goal of the program was to produce a pressure and vacuum tight joint, without mechanical fasteners, which was structurally reliable at temperatures ranging from room temperature to -320°F. This goal was achieved by the use of diffusion welding.

In 1965-66 a second development program(2) included the investigation of joining six dissimilar alloy combinations by diffusion welding. The six metal combinations were as follows:

1. 2219 Aluminum Alloy to AISI Type 321 Stainless Steel
2. 7106 Aluminum Alloy to AISI Type 321 Stainless Steel
3. 2219 Aluminum Alloy to Ti-5Al-2.5Sn Titanium Alloy
4. AISI Type 321 Stainless Steel to Ti-8Al-1Mo-1V Titanium Alloy
5. AISI Type 321 Stainless Steel to Inconel 718 Alloy
6. Inconel 600 to Ti-8Al-1Mo-1V Titanium Alloy

The goals of the program were to develop (1) a basic understanding of diffusion welding, (2) practical processing controls for production, and (3) joint property data at elevated and cryogenic temperatures. These goals were achieved and the results showed that all six material combinations could be joined in the bare condition or with silver electroplated surfaces.

The goals of this program were to verify that the previously developed welding processing techniques were adaptable to production hardware and to develop joint design data (such as, strength and fatigue properties) for the tubular joints at both room temperature and -320°F. The development work was conducted in two phases. The major part of the work was conducted in Phase I where tubular transition joints having diameters of 0.50, 2.0, 4.0 and 8.0-inches were manufactured from the following alloy combinations:

1. 2219 Aluminum Alloy to AISI Type 321 Stainless Steel
2. 2219 Aluminum Alloy to Ti-5Al-2.5Sn Titanium Alloy
3. AISI Type 321 Stainless Steel to Ti-8Al-1Mo-1V Titanium Alloy

In Phase II, an investigation was made to determine potential applications of diffusion welding for joining metals to meet aerospace design requirements. In this phase, laboratory work was conducted in sufficient depth to verify if the new applications were amenable to the diffusion welding process. Also, a literature review was maintained to keep abreast of new developments in solid state welding of dissimilar metals.

CONCLUSIONS

1. Tubular joints, 0.5 to 8.0-inch in diameter, of the following dissimilar metal combinations can be successfully made by diffusion welding using adaptations of processes developed for flat specimens:

   a. 2219 aluminum allloy to AISI type 321 stainless steel
   b. 2219 aluminum alloy to Ti-5Al-2.5Sn titanium alloy
   c. AISI type 321 stainless steel to Ti-8Al-1Mo-1V titanium alloy

2. The structural integrity of each joint combination was demonstrated and design data developed by successful completion of the following tests:

   a. Thermal shock
   b. Helium leak
   c. Random and sinusoidal dwell vibration testing
   d. Pressure cycling
   e. Pressure burst testing

3. Split outer dies should be used for diffusion welding of tubular joints to facilitate easier removal of the inner die and also to allow the use of nickel-base alloy inner mandrels.

4. Welded and drawn titanium tubing should be used for diffusion welded tubular joints including a titanium alloy component, in order to maintain the required diametrical concentricity tolerances necessary for intimate contact..

5. Nondestructive testing techniques, particularly ultrasound, must be refined in order to provide reliable post-weld joint inspection.

6. Diffusion welding has considerable potential for joining applications other than tubular transition joints, particularly for composite forms such as, sheet or forgings fabricated from laminates of similar or dissimilar metals.

PHASE I MANUFACTURING AND TESTING OF TUBULAR JOINTS

In the first phase of the program dissimilar metal tubular joints were joined by diffusion welding for evaluation by thermal shock, helium leak, vibration and cyclic pressure and burst tests. Manufacturing of the parts was performed using a silver electroplated diffusion aid and differential thermal expansion tooling[1,2].

JOINT DESIGN

Tubular joints having diameters of 0.5, 2.0, 4.0 and 8.0-inches were manufactured from the following material combinations:

1. 2219 Aluminum Alloy to AISI Type 321 Stainless Steel
2. 2219 Aluminum Alloy to Ti-5Al-2.5Sn Titanium Alloy
3. AISI Type 321 Stainless Steel to Ti-8Al-1Mo-1V Titanium Alloy

These three combinations were chosen from a group of six alloy combinations evaluated previously[2].

The tubular joints were designed using the material allowables shown in Figures 1 through 4. The design allowables used for 2219-T6 were reduced 15% from that shown in Figure 1 to compensate for the effect of overaging during diffusion welding at 500°F.

The joint configuration used for the tubular joints are shown in Figures 5 and 6. Since the tubular joints were for use primarily at room temperature and below, the material having the highest thermal contraction rate was used for the outer tubular member for all material combinations. The detail dimensions chosen for the parts are shown in Table I.

The joint overlap, L_1, was based on a shear stress estimated at 15,000 psi for tubular joints not having peel loading. The dimensions for T_3, L_2 and L_3 were based on the criteria that during pressure cycling, the deflections occurring in the joint area must be controlled to prevent peel loading at the joint area. The anticipated deflection profile is shown schematically in Figures 5 and 6.

TOOL DESIGN

The principle of differential thermal expansion was used for applying the welding pressure to the tube lap joint. The tooling arrangement for the 0.50-inch diameter joint is shown in Figure 7. An inner mandrel was not used because of the small tube diameter. Instead the inner tube was used with the end solid as shown in Figure 7. The solid end acted as the inner mandrel to withstand the high compressive force during diffusion welding. After diffusion welding, the part required additional machining to the configuration shown in Figure 5.

The 2.0, 4.0 and 8.0-inch diameter tubular joints were joined using the tooling configuration as shown in Figure 8. An age hardenable nickel base alloy is the most desirable material for an inner mandrel because of its resistance to deformation by compressive forces during diffusion welding. A 300 series stainless steel is also usable for an inner mandrel because of its higher rate of thermal contraction which aids in part removal from the tooling after diffusion welding. However, the stainless steels will deform during diffusion welding and will have a fairly short tool life. In this program the 300 series stainless steel was usually used for the mandrel material.

MANUFACTURING

0.50-Inch Diameter Parts

All parts for the 0.50-inch diameter tubular joints were machined from bar stock. The parts were initially machined to the configuration shown in Figure 7. After machining the parts were silver electroplated at the joint overlap area on both the inside diameter of the outer tube and on the outside surface of the inner tube. The procedures used for electroplating are outlined in Appendix A.

Immediately prior to diffusion welding, the silver electroplated surfaces were abrasively cleaned and wiped with acetone. The parts were assembled for diffusion welding using the procedures and tooling shown in Figure 7. All three alloy combinations were diffusion welded in an air atmosphere at 600°F and were held at temperature for 1 hour.

Five specimens were manufactured for each alloy combination. After diffusion welding the parts were machined to the configuration shown in Figure 5.

2.00, 4.00 and 8.00-Inch Diameter Parts

Material Preparation

All of the outer 2219 aluminum alloy parts were machined from rolled and square butt electron beam welded plate. After welding the tubes were solution heat treated and sized by pressing the tubes through a sizing die. The tubes were aged to the T6 condition prior to machining.

The 2.00 and 4.00-inch diameter outer AISI Type 321 stainless steel tubes were machined from seamless steel tubes. The 8.00-inch diameter outer tubes were machined from rolled and square butt electron beam welded plate. The welded tubes were annealed and sized prior to machining.

The 2.00 and 4.00-inch diameter inner stainless steel parts were made from 0.065-inch wall seamless tubing. The 8.0-inch tubing was made from rolled and GTA welded 0.065-inch thick sheet.

The 2.00, 4.00 and 8.00-inch diameter titanium alloy inner tubes were made from rolled (brake formed) and GTA square butt welded sheet. The Ti-5Al-2.5Sn alloy was 0.081-inch thick and the Ti-8Al-1Mo-1V alloy was .060-inch thick.

After machining all parts were silver electroplated at the joint overlap area on both the inside diameter of the outer tubes and on the outside diameter of the inner tubes (Appendix A).

Diffusion Welding

Diffusion welding was accomplished using the tooling arrangement shown in Figure 8. Prior to welding the silver electroplated surfaces were abrasively cleaned and wiped with acetone. Both Inconel 750 and AISI Type 321 stainless steel were used for the inner mandrel. The Inconel 750 inner mandrel was difficult to remove because its coefficient of thermal expansion is similar to the H-11 tool steel outer mandrel. The AISI type 321 stainless steel inner mandrel was easy to remove because of its high coefficient of thermal expansion. However, the low strength of stainless steel permits the mandrel to deform and limits its use to the manufacture of about 3 to 5 tubular assemblies.

Diffusion welding was conducted at the following temperature and time cycles:

1. 2219 Al to AISI Type 321 SS - 500°F for 2 hours
2. 2219 Al to Ti-5Al-2.5Sn - 600°F for 1 hour
3. AISI Type 321 SS to Ti-8Al-1Mo-1V - 700°F for 30 minutes

After welding the tooling was removed from the furnace. The inner mandrel was cooled with liquid nitrogen for approximately 15 minutes prior to removal from the assembly. A pressing force varying from 500 to 5,000 pounds was usually required. After removing the inner mandrel (outer die still hot) the tubular assembly was chilled with liquid nitrogen and lifted from the outer die. Figure 9 shows the appearance of completed joints.

INSPECTION

After manufacturing all parts were subjected to helium leak check. Those parts which were leak tight were subjected to a thermal shock test 5 times. This was conducted by heating the parts to 180°F and submerging in liquid nitrogen. After this test the parts were checked with a helium leak detector. Specimens which were found to leak were subjected to peel testing and/or metallurgical examination.

From the inspection procedure the following was observed:

1. None of the 0.50-inch diameter tubular joints contained a helium leak before or after the thermal shock tests.

2. None of the 2.0, 4.0 and 8.0-inch diameter 2219 aluminum alloy to AISI type 321 stainless steel tubular joints contained a helium leak before or after the thermal shock tests.

3. Approximately 25% of the 2.0, 4.0 and 8.0-inch diameter tubular joints which contained a titanium alloy inner tube contained a helium leak when inspected after joining. No additional leaks in any part were found after thermal shock tests.

4. Peel testing and metallurgical examination of the tubular joints which leaked revealed the cause to be longitudinal flat areas on the titanium tube which did not contact the outer tube during diffusion welding. These flat areas originated by the brake forming operation during manufacturing of the titanium tubing.

5. Several of the defective diffusion welded joints (the leaks) were subjected to metallurgical examination to determine if the quality of the silver electroplating contributed to the occurrence of the defective areas. This examination revealed that the plating was of acceptable quality and well diffused to the tubing materials. All defective areas and/or leaks were located where the silver electroplated surfaces failed to come into intimate contact during diffusion welding.

6. Several of the titanium tubes were "hot sized" prior to their use in diffusion welded joints. This was performed at 1300°F while having a stainless steel mandrel pressed into the tubing. This procedure improved the roundness of the titanium and helped to decrease the number of tubular joints which contained a helium leak after joining.

TESTING

After inspection of the tubular joints, two parts from each size and alloy combination were selected for vibration, pressure cycling and burst testing. Figure 10 summarizes the sequential flow used for testing the specimens. The results of the tests are shown in Tables II, III, and IV.

Vibration

Vibration tests were conducted on 2.0 and 8.0-inch diameter parts. The specimens were prepared for test by welding a mounting flange to the base of the outer tube and by welding an extension to the inner tube as shown in Figure 11. The length of the tube extension used for each size is shown on the tabulation in Figure 11. The selection of the tube length was based on calculations which predicted the stress at the outer tube root during random vibration using the power input spectrum shown in Figure 12. A tube length was selected which would limit the maximum root stress to approximately the fatigue limit of the outer tube material (20 KSI for 2219 Al, 30 KSI for AISI type 321 SS). The predicted stress levels are shown in Table V. The tubular joints were tested in vibration using a vibration system and arrangement as shown in Figures 13 and 14.

The tubes were subjected to random vibrations for 15 minutes using the power input spectrum shown in Figure 12. During testing, 3 of the 2.0-inch diameter tubes having an aluminum outer tube failed in the tube root outside the joint area. Additional tubes were tested using a rubber mounted clamp placed around the aluminum tube to limit the bending stress at the tube root. With this modification specimens A8, A9, B7 and B8 (Tables II and III) successfully survived the random vibration test. All other 2.0 and 8.0-inch diameter parts survived the random vibrations without this modification. Power spectral density curves for each part are shown in Appendix B.

After random vibration all tubes were tested in sinusoidal dwell at part natural frequency for 10^5 cycles. A 5G peak input was used for the 2.0-inch diameter parts and a 7.5G peak input was used for the 8.0-inch diameter parts.

Helium Leak Test

After vibration testing the 2.0 and 8.0-inch diameter parts were checked for leaks using a helium leak detector. All parts were leak free including the three 2.0-inch diameter parts which failed in the tube root.

Cyclic Pressure

The tubular joints (except for the AISI type 321 stainless steel to Ti-8Al-1Mo-1V titanium combination) were cyclic pressure tested at both ambient temperature and -320°F for 200 cycles in accordance to the cyclic pressures shown in Tables II and III. Cyclic pressure testing of each AISI type 321 stainless steel to Ti-8Al-1Mo-1V titanium tubular joint was conducted only at ambient temperature in accordance to the cyclic pressures shown in Table IV.

Helium Leak Test

All parts were helium leak tight after completion of the cyclic pressure tests.

Burst Test

One tubular joint from each size and alloy combination was set up for burst testing at room temperature and at -320°F. None of the 0.50 and only one of the 2.0-inch diameter parts burst at -320°F because of the limited capacity (7000 psig) of the liquid nitrogen pump. These parts (total of 5) were all subjected to the 7000 psig maximum pressure of the liquid nitrogen pump and then pressurized to burst at room temperature. The appearance of each specimen after burst is shown in Figures 15 through 26.

Metallurgical Examination

Typical 0.5 and 2.0-inch diameter tubular joints from each of the three dissimilar metal combinations were subjected to thorough metallurgical examinations. The 4.0 and 8.0-inch diameter tubular joints were examined visually. The metallurgical characteristics between the 2.0, 4.0, and 8.0-inch diameter joints were considered to be basically the same because of the similar processing and tooling concepts. In addition, the joint peel tests indicated that the peel characteristics of the 2.0, 4.0 and 8.0-inch diameter joints were almost identical. In general, the metallurgical characteristics of the three diffusion welded joints were basically the same as the particular three corresponding dissimilar metal combinations studied previously(2).

1. 2219 Aluminum Alloy to AISI Type 321 Stainless Steel

   Figures 27 and 28 illustrate the joint microstructure of this combination for the 0.5 and 2.0-inch diameter tubular joints, respectively. The microstructures are similar, with complete interdiffusion (such as, grain growth and recrystallization) occurring across the original silver electroplate interface. The major diffusion zone development is at the 2219 aluminum alloy to silver electroplate interface. This diffusion zone is only approximately 1 micron (0.00004-inch) in thickness. Previous studies have shown this thickness not to be detrimental to joint characteristics(2).

   Examination of the tubular joints that failed by shearing during burst testing revealed that failure occurred by random propagation along the original Ag-Ag or Ag-Al interfaces.

2. 2219 Aluminum Alloy to Ti-5Al-2.5Sn Titanium Alloy

   The microstructures of the 0.5 and 2.0-inch diameter tubular joints for the 2219 aluminum alloy to Ti-5Al-2.5Sn titanium alloy combination are shown in Figures 29 and 30, respectively. Again there has been complete interdiffusion across the silver electroplate interface. Acceptable interdiffusion is shown between the Al-Ti and Ag-Al interfaces. The prediffusion treatment of the silver electroplate to the Ti-5Al-2.5Sn alloy interface resulted in complete diffusion of these systems. Examination of the tubular joints that sheared during burst testing indicated that fracture occurred primarily along the original Ag-Ag interface. Small areas of failure at the Ag-Ti interface were also noted.

3. AISI Type 321 Stainless Steel to Ti-8Al-1Mo-1V Titanium Alloy

   Figures 31 and 32 illustrate typical microstructures of the 0.5 and 2.0-inch diameter joints, respectively, for the AISI type 321 stainless steel to Ti-8Al -1Mo-1V titanium alloy combination. Complete interdiffusion occurred at the Ag-Ag electroplate interface with acceptable diffusion and phase development occurring at the Ti-Ag and stainless steel-Ag interfaces. Prediffusion of the Ag electroplate into Ti is acceptable. Analysis of the fractures that sheared during burst testing revealed primary propagation along the original Ag-Ag interface.

EVALUATION OF PROGRAM

After completion of the program the results of the manufacturing and test programs were evaluated to determine the success of the program.

Manufacturing

Difficulty was experienced in removing the tubular parts from the outer die when Inconel 750 was used for the inner mandrel. The substitution of stainless steel for the mandrel material, because of its higher coefficient of thermal contraction, eliminated this problem. However the stainless steel mandrel, because of its low yield strength, deformed and was not suitable for use after manufacturing 3 to 5 parts. In future programs the outer die should be split (similar to the 0.50-inch parts) particularly on the 2.0 and 4.0-inch diameter parts. This will permit easy removal of the inner die and facilitate the use of the Inconel 750 alloy.

The difficulty experienced in making leak tight joints in the combinations containing a titanium alloy inner tube were traced directly to tube quality. Because of the high strength of the titanium alloys at the diffusion welding temperature they would not yield and conform to the roundness of the tooling. Because of this the titanium tubing must be initially round within the required tolerance and free of flat spots. In future programs welded and drawn tubing should be used instead of the rolled and welded tubing used in this program.

In general, the manufacturing program was successful. With improved titanium tubing, the manufacturing techniques used in this program are capable of reliably producing void free joints.

Testing

Vibration and Cyclic Pressure

The vibration test program was considered successful. The three 2.0-inch diameter tubular joints which failed in vibration resulted from overstressing of the tube root and not from joint defects. Each specimen successfully passed a rigorous vibration and cyclic pressure testing without failure and without developing helium leaks in the diffusion welded joint.

Burst Testing

Burst test results are summarized in Table VI. From examination of these results and of the actual failed parts the following observations were made:

1. All tubular joints, except specimen B15 and C15, C20 (Tables II and III) failed at or near their estimated burst pressure.

2. Specimen B15 was the only specimen which contained a substandard diffusion welded joint. Examination of the joint after failure revealed the joint contained approximately 40 percent of defective area. The defective area resulted from flat spots in the tubing which failed to allow intimate contact with the outer tube during welding.

3. Specimen C15 failed prematurely by shearing of the diffusion welded joint. Examination of the welded joint showed that it was completely welded. The failure was believed due to the stainless steel outer tube expanding excessively during pressurization resulting in a peel-type failure.

4. Specimen C20 failed at a low pressure because a premature failure of the titanium head weld where it intersected the tube longitudinal weld.

In general the burst tests were successful and have substantiated that dissimilar metal tubular transition joints are capable of meeting design requirements.

Metallurgical Examination

Metallurgical examinations of representative joints showed that the diffusion weld quality is similar to that obtained in the previous work[1,2]. These examinations showed that the electroplating, pre-diffusion, cleaning and joining techniques are reproducible and acceptable for incorporation into production process.

Nondestructive Testing

Limited testing performed with ultrasound techniques has shown that this method does not detect all defective joint areas. The process used did locate the larger areas which were not in contact, but did not locate the small, partially unwelded areas. Nondestructive testing techniques, particularly ultrasound, must be refined in order to provide reliable post-weld joint inspection. Presently, strict in-process control plus statistical testing are the best methods for assuring a reliable diffusion weld product.

PHASE II JOINING OF COMPOSITE FORMS

In the second phase of the program work was conducted to determine where diffusion welding could be used to join metals for aerospace design requirements. This work has shown that the most pressing requirement is for tubular transition joints for use in pressure lines. Other areas of interest and possible use for diffusion joining similar or dissimilar metals are electrical connections where brazing or soldering is undesirable, composites for the control of heat flow or to improve machinability as well as heat and wear resistance. The area which appears to have the greatest potential is that of diffusion welding laminate sheet, plate, and forgings out of both similar and dissimilar metals. This technique permits the improvement of directional properties, fracture toughness, and corrosion properties of the material.

LAMINATION OF METALS

Several metal combinations were laminated by roll welding. This was accomplished by sealing the materials in an inert gas purged steel sheath and rolling at elevated temperatures. Material combinations were successfully joined as follows:

Titanium to Aluminum
Titanium to Stainless Steel

The titanium alloys were successfully joined to aluminum alloys using a rolling temperature of 850°F. Titanium and stainless steel were joined by using a pure aluminum foil at the joint interface and a rolling temperature of 850°F. The laminated sheets contained excellent peel strength and formability.

Titanium to Titanium

Titanium alloy forgings are expensive because of the forging cost and of the high ratio of forging to finished machined part weight. The production of heavy sections by laminating sheet offers many advantages such as an improvement in directional properties, the close control of temperature to prevent processing above the beta-transus, the laminating of dissimilar titanium alloys to control toughness and strength and a considerable savings in raw material costs.

Work conducted on joining titanium alloys by diffusion welding showed that at temperatures of approximately 1800°F welding pressures of only 100 to 250 psi are adequate to produce void-free joints. The photomacrograph shown in Figure 33 is one example of this work. The test work conducted has demonstrated that the production of a heavy titanium section by laminating sheet is feasible.

Beryllium to Beryllium

Beryllium foil, made from ingot sheet, has been produced which possess good ductility and formability. This foil has been used to laminate thicker sections by using aluminum foil interleaf and rolling the laminate at 1000°F. Peel testing and metallurgical examination of the laminated section indicated the interfaces contained a metallurgical bond having good strength and ductility. Photomicrographs of the laminates are shown in Figure 34. Radiographic examination of the laminations did not reveal any cracking of the beryllium. Specimens cut from laminated sheet possessed good formability. The 0.03-inch thick lamination was formed to a 7T radius without cracking when tested at 500°F.

JOINING FOR THERMAL AND ELECTRICAL CONDUCTION

Methods are required to join both similar and dissimilar metals for purposes of conducting heat and electricity. Diffusion welding can be used for these applications when soldering or brazing is considered undesirable. Diffusion welding was evaluated for solar cell panel applications which required copper strips to be joined to an aluminum frame. Diffusion welded joints were readily obtained by silver electroplating the faying surfaces of both materials and by the application of heat and pressure. This was performed using flat dies (5/8" diameter) in a hot dimpling machine. The dies were preheated to 800°F and welding was accomplished in 15 seconds using a pressure which compressively decreased the joint thickness by 0.003-inch. The joints were void-free and exhibited excellent peel strength.

INCONEL 600 TO INCONEL 600

Components for hydraulic and pneumatic control devices often require the joining of intricate parts containing small ports and passages for the flow of oil or gas. Brazing of these ports is difficult because stop-off materials are normally not permitted because of contamination. Brazing without stop-off often results in partial or complete plugging of the passages. Methods were developed for high temperature-low pressure diffusion welding of these ports. The low pressure is necessary to prevent deformation of the machined ports.

Inconel 600 was joined by using gold foil for a diffusion aid. Diffusion welded joints were obtained using a temperature of 1775°F, a time of 15 minutes, and a pressure of 50 psi. Figure 35 shows the appearance of the joint.

TABLE I - JOINT CONFIGURATION DATA

D Inch	Inner Tube Alloy	Outer Tube Alloy	Joint Dimensions - Inches									Pressure, PSIG			
			T_1	T_2	T_3 (min)	T_4	L_1	L_2	L_3	L_4 (min)	L_5 (min)	Cyclic		Burst	
												RT	-320°F	RT	-320°F
0.50	321 SS	2219 T6 Al*	.050	.040	.140	.080	.40	.60	.50	2.5	2.5	4430	5475	8,960	10,950
2.00			.060	.100	.140	.200	.80	1.00	1.00	4.0	4.0	1920	2875	4,720	5,750
4.00			.060	.100	.140	.200	1.00	1.25	1.00	6.0	6.0	945	1430	2,340	2,860
8.00			.060	.100	.140	.200	1.00	1.25	1.00	8.0	8.0	470	713	1,170	1,425
0.50	Ti-5Al-2.5Sn	2219 T6 Al*	.050	.040	.100	.080	.40	.60	.50	2.5	2.5	4480	5475	8,960	10,950
2.00			.080	.100	.140	.200	.80	1.00	1.00	4.0	4.0	1920	2875	4,720	5,750
4.00			.080	.100	.140	.200	1.00	1.25	1.00	6.0	6.0	945	1430	2,340	2,860
8.00			.080	.100	.140	.200	1.00	1.25	1.00	8.0	8.0	470	713	1,170	1,425
0.50	Ti-8Al-1Mo-1V	321 SS	.050	.030	.030	.045	.40	.60	.60	2.5	2.5	4440	-	11,100	24,900
2.00			.060	.060	.060	.090	.80	1.00	.75	4.0	4.0	1850	-	4,650	10,400
4.00			.060	.070	.060	.090	1.00	1.25	.75	6.0	6.0	1070	-	2,670	6,000
8.00			.060	.080	.060	.120	1.00	1.25	1.00	8.0	8.0	604	-	1,510	3,380

*Based on over-aged 2219-T6 material properties (exposed to 500°F - 2 hours).

TABLE II SUMMARY OF TEST PROGRAM (2219 Aluminum Alloy to AISI Type 321 Stainless Steel)

Spec. No.	Joint Dia. Inch	Thermal Shock +180°F to -320°F	Helium Leak Test	Vibration			Helium Leak Test	Cyclic Pressure		Helium Leak Test	Burst Test	
				Random Min.	Sinusoidal Frequency cps	Sinusoidal Time (min.)		72°F 200 Cycles PSIG	-320°F 200 Cycles PSIG		72°F PSIG	-320°F PSIG
A1		5 Times	x	-	-	-	x	4480	5475	x	8100	
A2		"	x	-	-	-	x	4480	5475	x	6600	[1]
A3	0.5	"	x									
A4		"	x									
A5		"	x	Spare								
A6		5 Times	x	14.8 [2]			x					
A7		"	x	6 [2]			x					
A8		"	x	15	263	6.3	x	1920	2875	x	4400	
A9	2.0	"	x	15	216	7.7	x	1920	2875	x		6150
A10		5 Times	x									
A11			x									
A12				Spare								
A13												
A14		5 Times	x	-	-	-	-	945	1430	x	1900	
A15		"	x	-	-	-	-	945	1430	x		2550
A16	4.0	"	x									
A17		"	x									
A18		"	x	Spare								
A19		5 Times	x	15	114	14.5	x	470	713	x	1375	
A20		"	x	15	115	14.5	x	470	713	x		1620
A21	8.0	"	x									
A22		"	x									
A23		"	x	Spare								

[1] Pressurized to 7000 PSI @ -320°F prior to R.T. burst

[2] Failed in root of specimen fitting.

TABLE III SUMMARY OF TEST PROGRAM (2219 Aluminum Alloy to Ti-5Al-2.5Sn Titanium Alloy)

Spec. No.	Joint Dia. Inch	Thermal Shock +180°F to -320°F	Helium Leak Test	Vibration			Helium Leak Test	Cyclic Pressure		Helium Leak Test	Burst Test	
				Random Min.	Sinusoidal Frequency cps	Sinusoidal Time (min.)		72°F 200 Cycles PSIG	-320°F 200 Cycles PSIG		72°F PSIG	-320°F PSIG
B1		5 Times	x	-	-	-	-	4480	5475	x	7700	
B2		"	x	-	-	-	-	4480	5475	x	8300 [1]	
B3	0.5	"	x									
B4		"	x									
B5		"	x	Spare								
B6		5 Times	x	11.3 [2]			x					
B7		"	x	15	212	7.7	x	1920	2875	x	3800	
B8		"	x	15	239	7.0	x	1920	2875	x		4460
B9	2.0	"	x									
B10		"	x									
B11			Leak	Crack in Titanium Longitudinal Weld								
B12			Leak	Peel Test								
B13				Spare								
B14		5 Times	x	-	-	-	-	945	1430	x	1875	
B15		"	x	-	-	-	-	945	1430	x		1600
B16	4.0											
B17												
B18			Leak	Peel Test								
B19		5 Times	x	15	140	11.9	x	470	713	x	1100	
B20		"	x	15	156	11.5	x	470	713	x		1408
B21			Leak	Crack in Aluminum Longitudinal Weld								
B22	8.0		x									
B23			x									
B24			x	Spare								
B25			Leak	Peel Test								
B26			x									

[1] Pressurized to 7000 PSI @ -320°F prior to R.T. test.
[2] Failed in root of specimen fitting.

TABLE IV - SUMMARY OF TEST PROGRAM (AISI Type 321 Stainless Steel to Ti-8Al-1Mo-1V Titanium Alloy)

Spec. No.	Joint Dia. Inch	Thermal Shock +180°F to -320°F	Helium Leak Test	Vibration: Random Min.	Vibration: Sinusoidal Frequency cps	Vibration: Sinusoidal Time (min.)	Helium Leak Test	Cyclic Pressure 72°F 200 Cycles PSIG	Cyclic Pressure -320°F 200 Cycles PSIG	Helium Leak Test	Burst Test 72°F PSIG	Burst Test -320°F PSIG
C1		5 Times	x	-	-	-	-	4400	-	x	11,600	
C2		"	x	-	-	-	-	4400	-	x	12,200 [1]	
C3	0.5	"	x									
C4		"	x									
C5		"	x	Spare								
C6		5 Times	x	15	194	8.5	x	1850	-	x	5,900	
C7		"	x	15	208	8.0	x	1850	-	x	6,150 [1]	
C8		"	x									
C9	2.0	"	x									
C10		"	x	Metallurgical Examination								
C11			Leak		Peel Test							
C12												
C13				Spare								
C14		5 Times	x	-	-	-	-	1070	-	x	3,020	
C15		"	x	-	-	-	-	1070	-	x		4,120
C16	4.0		x									
C17			x									
C18			Leak		Peel Test							
C19		5 Times	x	15	171	9.8	x	604	-	x	1,245	
C20		"	x	15	163	10.5	x	604	-	x		890
C21	8.0		x									
C22			x									
C23			Leak		Peel Test							

[1] Test duration 15 minutes.

TABLE V. PREDICTED SPECIMEN ROOT STRESS DURING RANDOM AND SINUSOIDAL VIBRATION TEST

TUBE DIA. (in)	MATERIAL COMBINATION	RANDOM VIBRATION ROOT STRESS psi [1]	SINUSOIDAL VIBRATION ROOT STRESS psi [2]
2.0	2219 Al to 321 SS	8,050	11,500
8.0		6,470	13,900
2.0	2219 Al to Ti-5Al-2.5Sn	7,000	10,000
8.0		6,200	13,300
2.0	321 SS to Ti-8Al-1Mo-1V	7,860	14,500
8.0		10,100	16,900

[1] Based on a RMS Stress $\approx$ 3.5 σ root.
Root stresses twice these values occurred approximately 17% of the time and 3 times these values occurred approximately 1% of the time.

[2] Based on a 5G peak for 2.0-inch diameter and a 7.5G peak for 8.0-inch diameter joints.

TABLE VI BURST TEST RESULTS

Specimen No.	Joint Dia. Inch	Material Combination	Burst Pressure, psig R.T. Estimated	Burst Pressure, psig R.T. Actual	Burst Pressure, psig -320°F Estimated	Burst Pressure, psig -320°F Actual	Outer Tube Hoop Stress At Failure psi	Failure Location
A1	0.50	2219 Al to 321 SS	8,200	8,160			42,000	Wall of Aluminum Tube
A2				6,600	10,600	[1]	39,600	Wall of Aluminum Tube
A8	2.0		4,200	4,400			44,000	Crack in Aluminum Tube
A9					5,500	6,150	61,500	Wall of Aluminum Tube
A14	4.0		2,100	1,900			38,000	Aluminum Head Weld
A15					2,750	2,550	51,000	Aluminum Head Weld
A19	8.0		1,050	1,375			55,000	Aluminum Tube at Joint
A20					1,380	1,620	65,000	Shear at Joint
B1	0.50	2219 Al to Ti-5Al-2.5Sn	8,200	7,700			40,000	Wall of Aluminum Tube
B2				8,300	10,600	[1]	43,000	Wall of Aluminum Tube
B7	2.0		4,200	3,800			38,000	Wall of Aluminum Tube
B8					5,500	4,460	44,600	Aluminum Head Weld
B14	4.0		2,100	1,875			37,500	Aluminum Head
B15					2,750	1,600	32,000	Shear at Joint
B19	8.0		1,050	1,100			44,000	Leak at Joint
B20					1,380	1,408	59,200	Wall of Aluminum Tube
C1	0.50	321 SS to Ti-8Al-1Mo-1V	11,100	11,600			78,500	Titanium Tube at Joint
C2				12,200	24,900	[1]	82,500	Wall of Stainless Steel Tube
C6	2.0		4,650	5,900			96,500	Wall of Stainless Steel Tube
C7				6,150	10,400	[1]	100,500	Wall of Stainless Steel Tube
C14	4.0		2,670	3,020			85,500	Shear of Joint
C15					6,000	4,120	114,000	Shear of Joint
C19	8.0		1,510	1,245			62,000	Shear of Joint
C20					3,380	890	44,200	Titanium Head Weld

[1] These tubes were pressurized to capacity of the pump - 7000 psig @-320°F, tubes then burst tested at R.T.

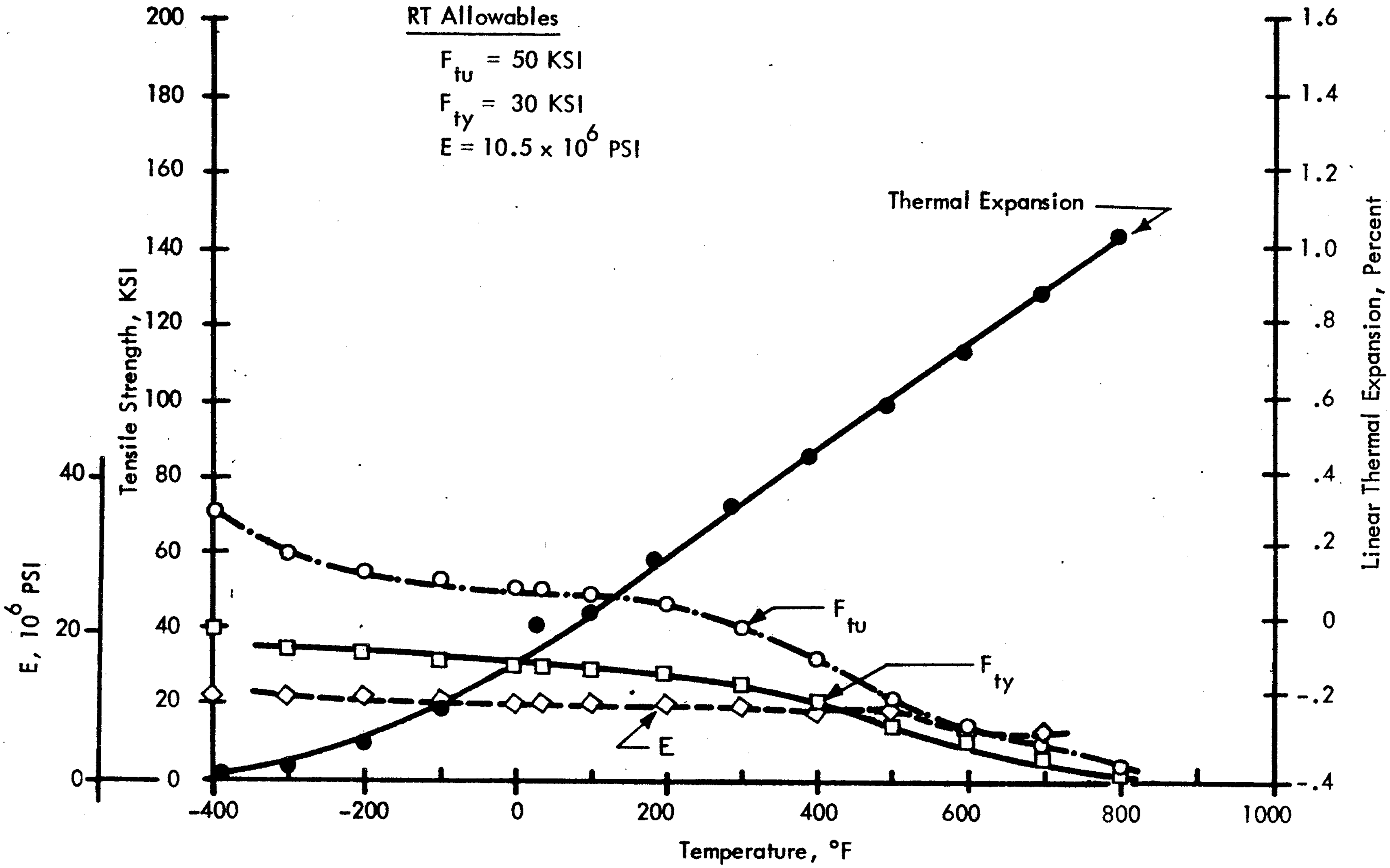


FIGURE 1 - STATIC MECHANICAL AND PHYSICAL PROPERTIES OF 2219 ALUMINUM ALLOY

Sheet - T62 Condition

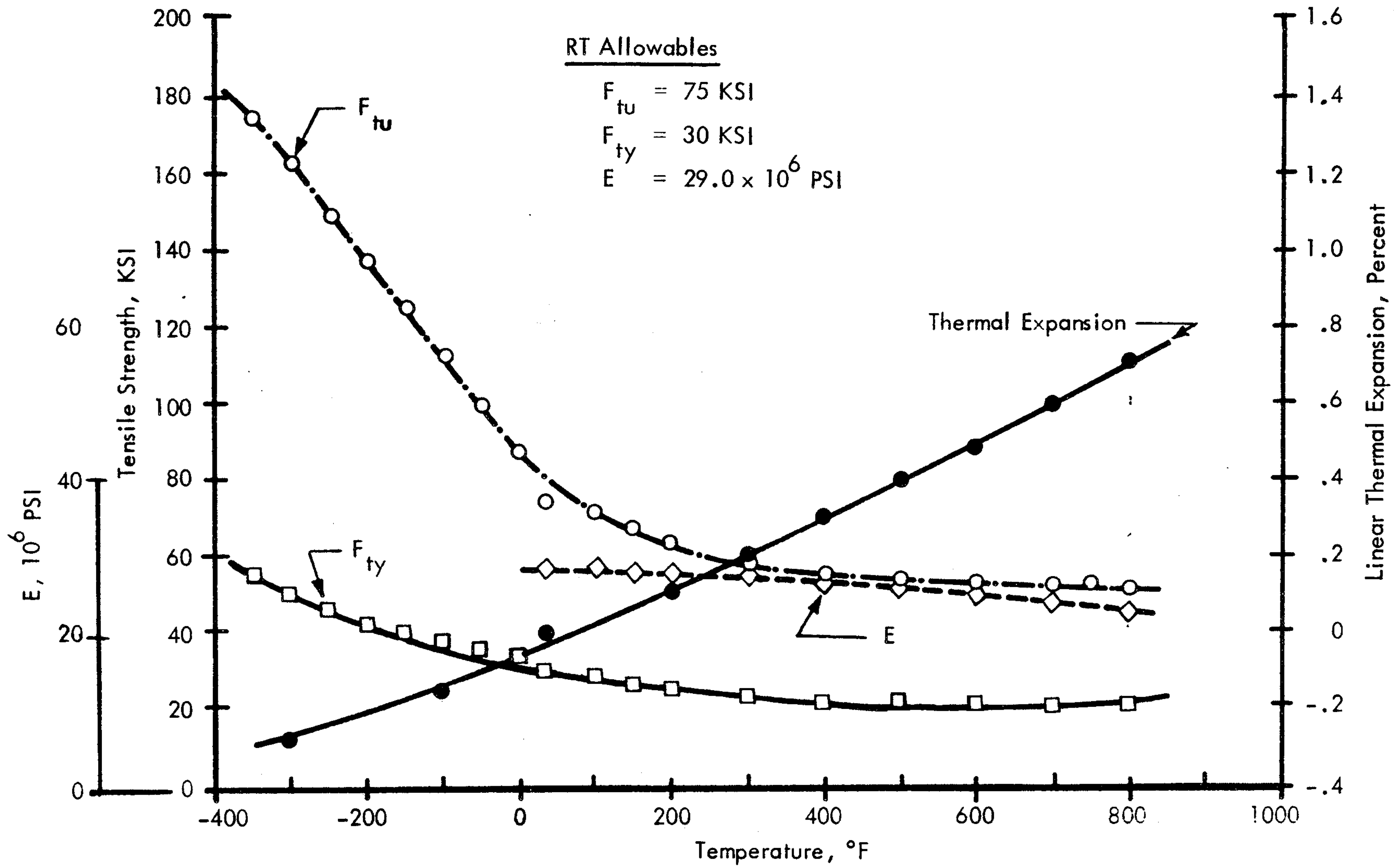


FIGURE 2 - STATIC MECHANICAL AND PHYSICAL PROPERTIES OF AISI TYPE 321 STAINLESS STEEL

- Annealed Sheet -

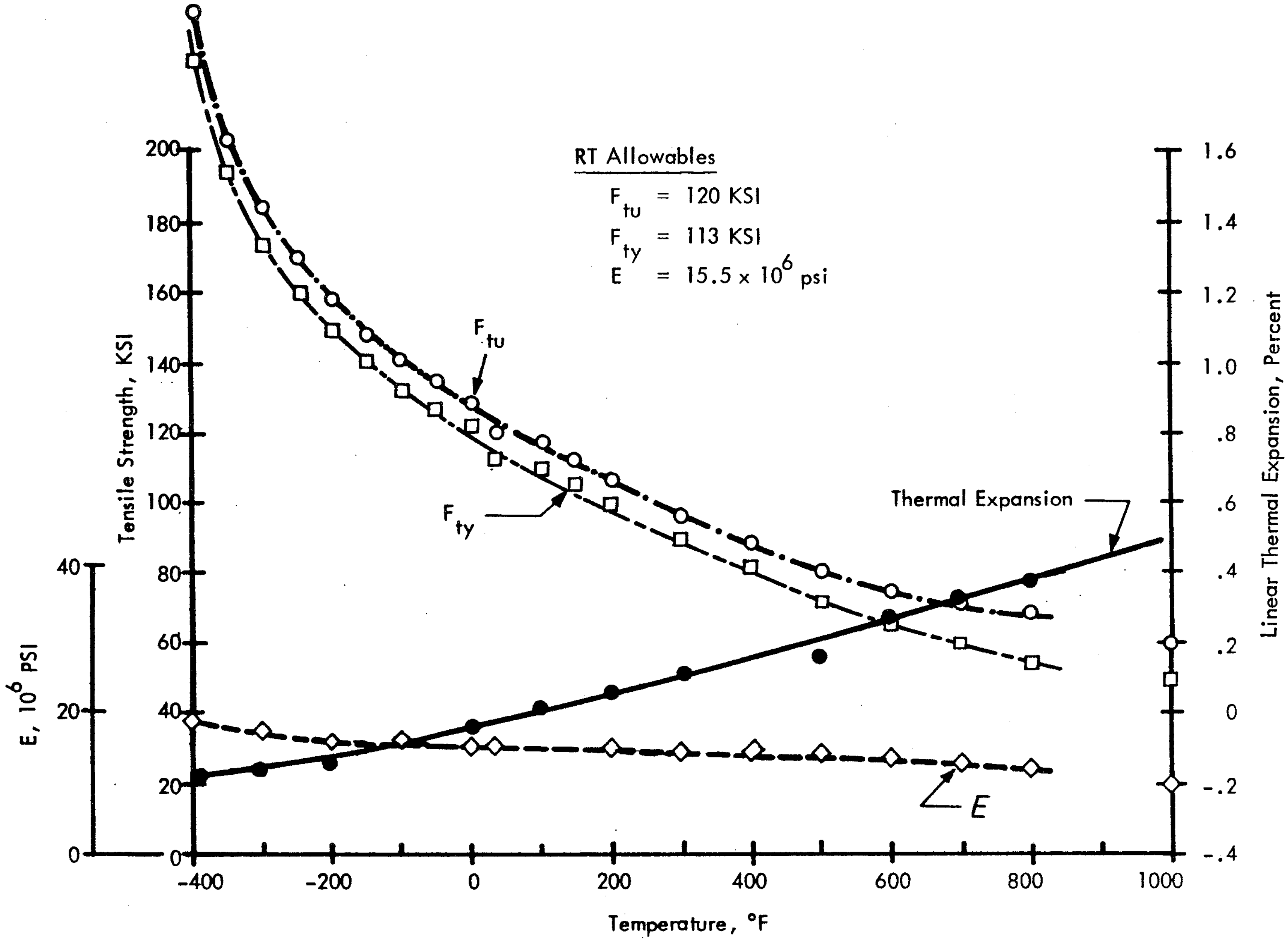


FIGURE 3 - STATIC MECHANICAL AND PHYSICAL PROPERTIES OF Ti-5Al-2.5Sn TITANIUM ALLOY

- Annealed Sheet -

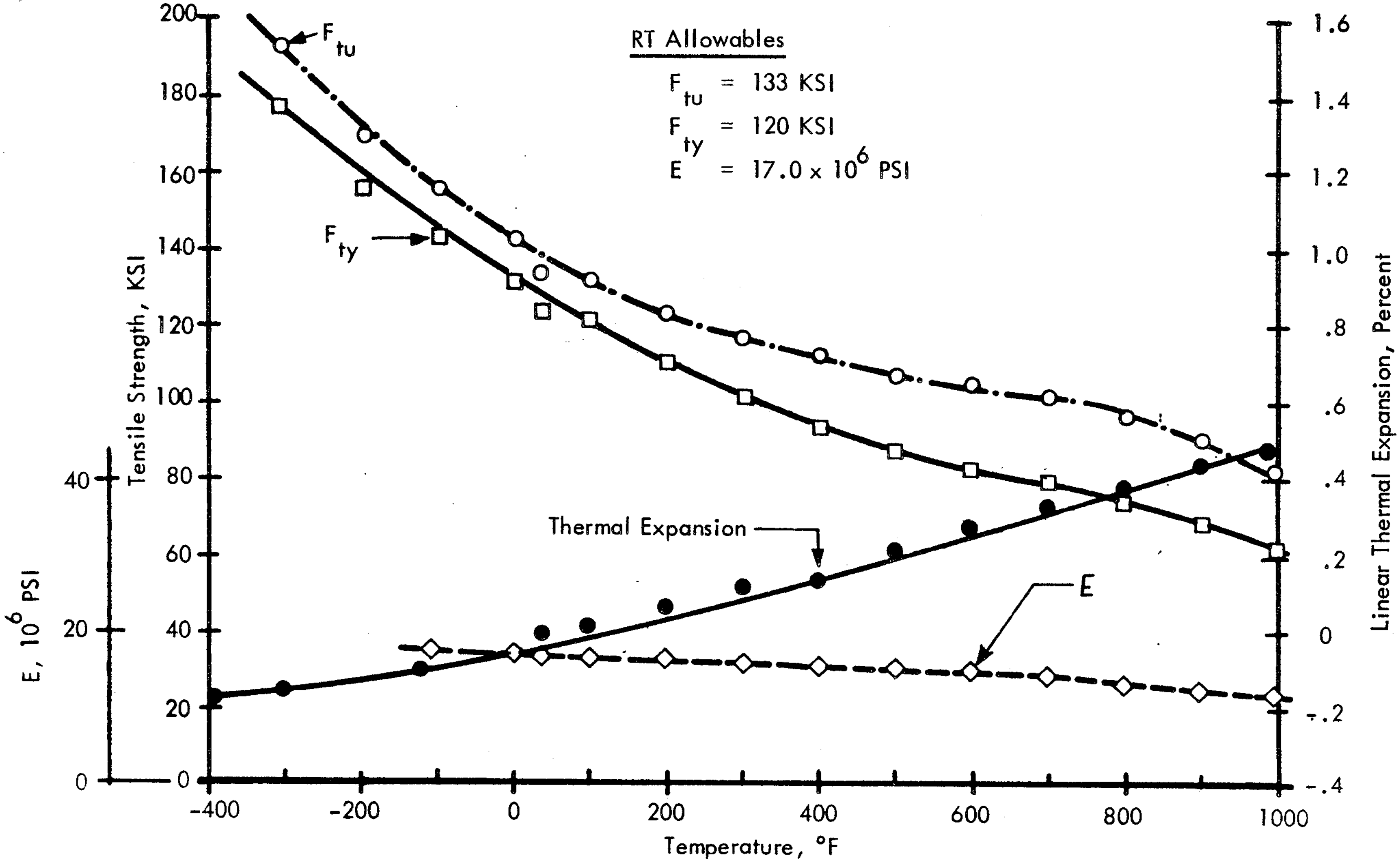


FIGURE 4 - STATIC MECHANICAL AND PHYSICAL PROPERTIES OF Ti-8Al-1Mo-1V TITANIUM ALLOY

- Duplex Annealed Sheet -

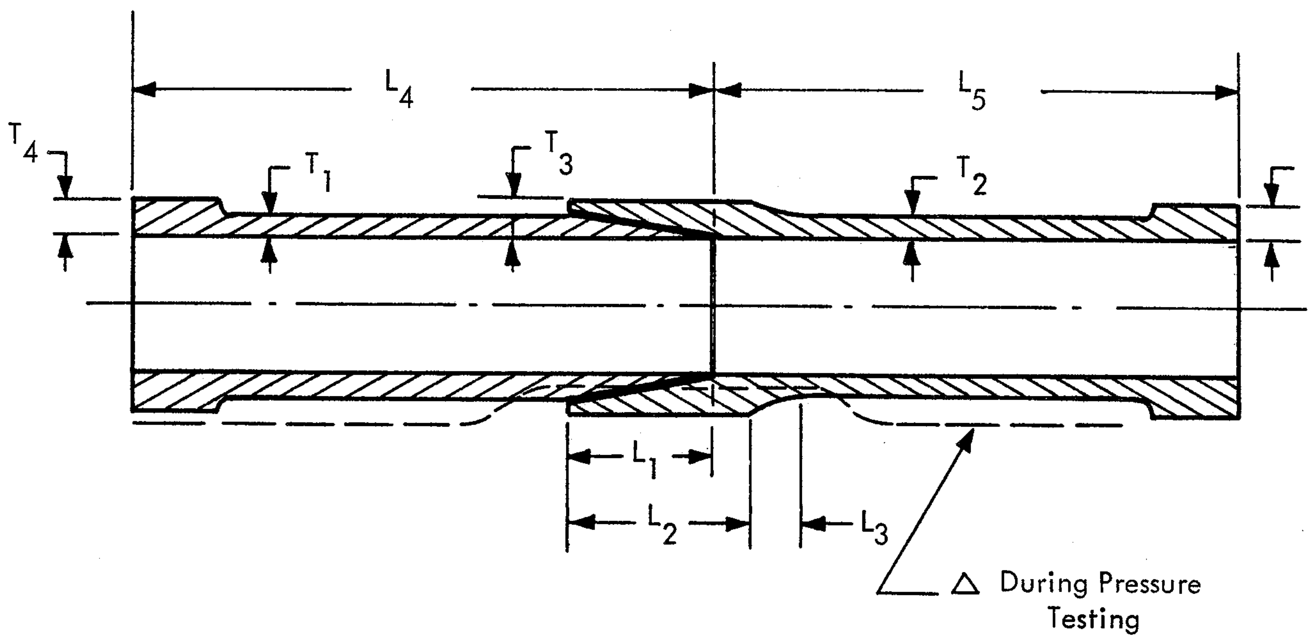


FIGURE 5 TUBULAR JOINT CONFIGURATION (0.50-INCH TUBE DIAMETER)

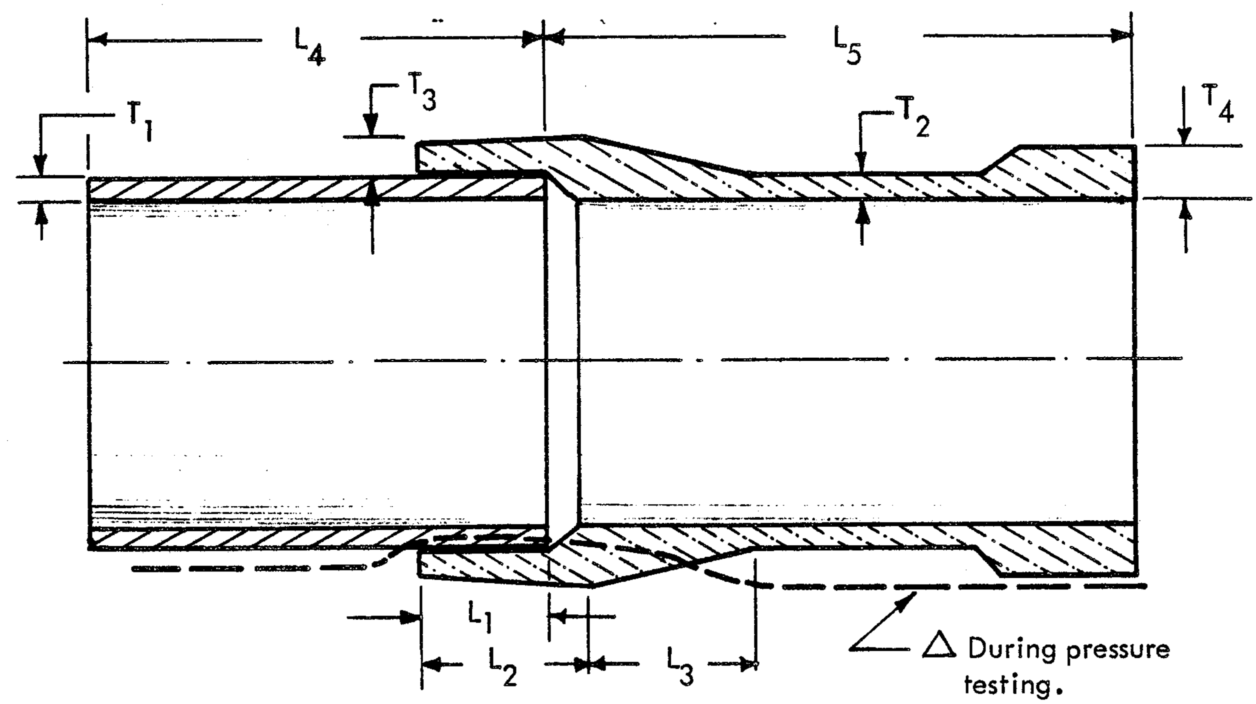
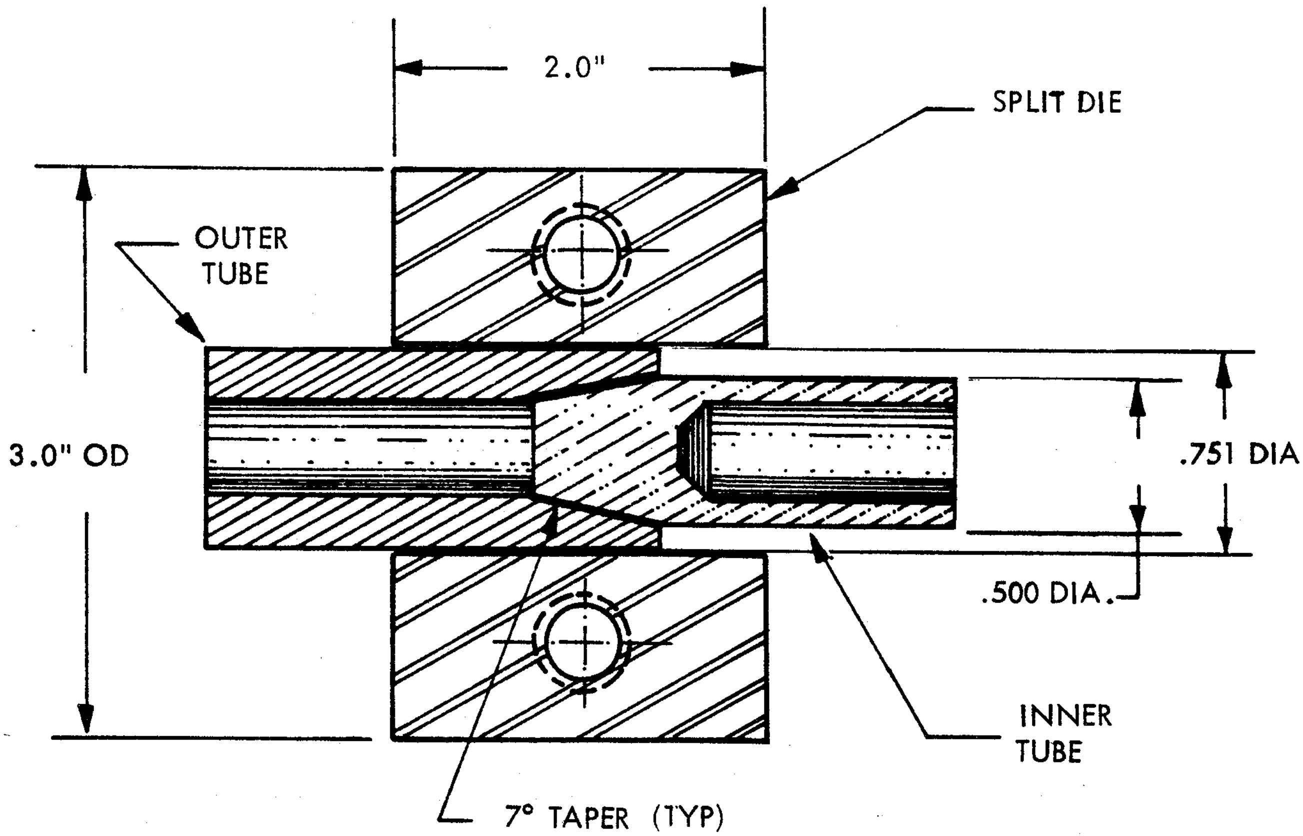


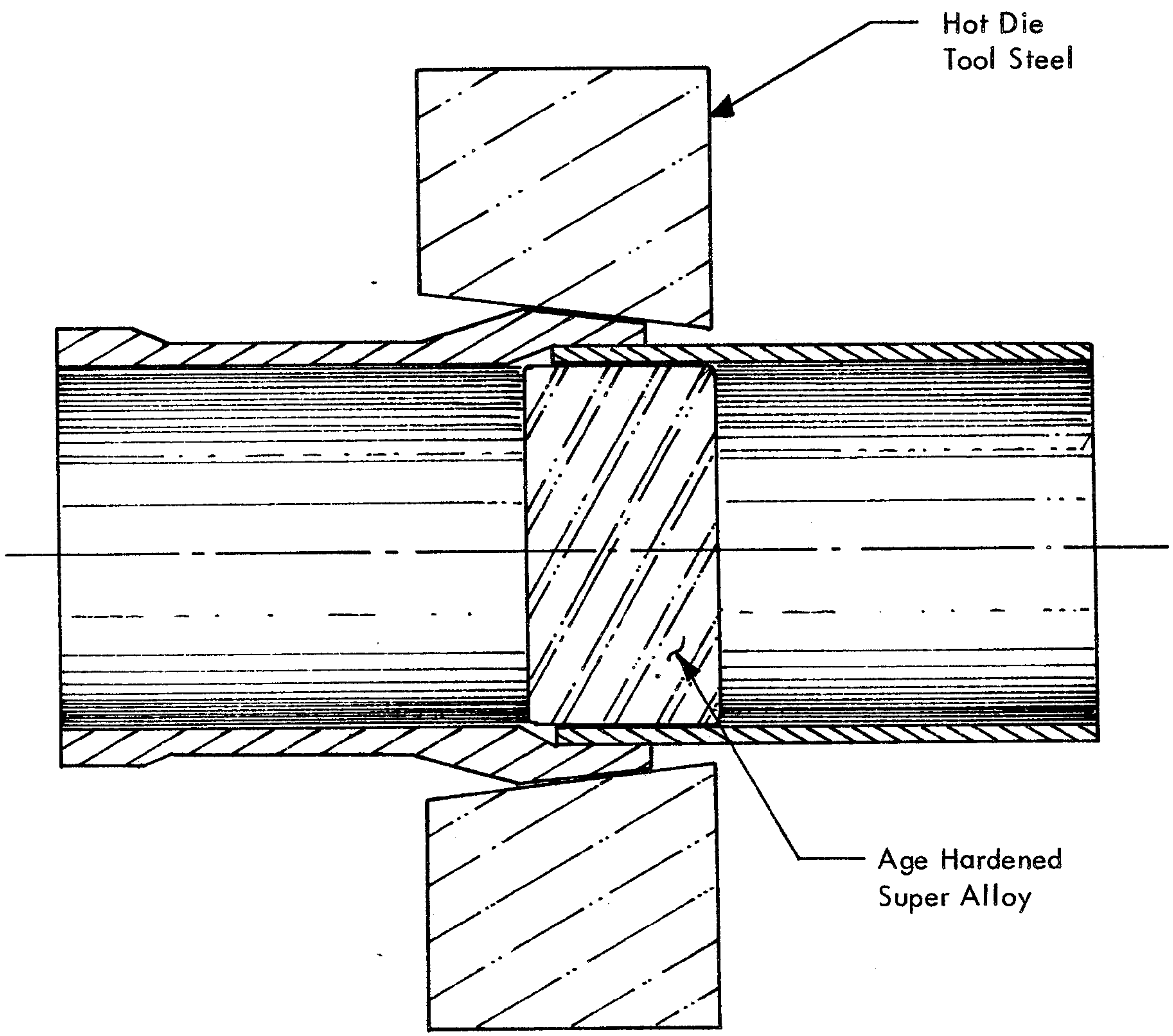
FIGURE 6 TUBULAR JOINT CONFIGURATION
(2.00, 4.00 and 8.00-Inch Tube Diameter)



ASSEMBLY PROCEDURE

1. Heat split die to 500°F
2. Insert outer tube into heated die
3. Cool inner tube to -320°F and press with 3000# axial load into outer tube
4. Stabilize temperature of assembly prior to welding

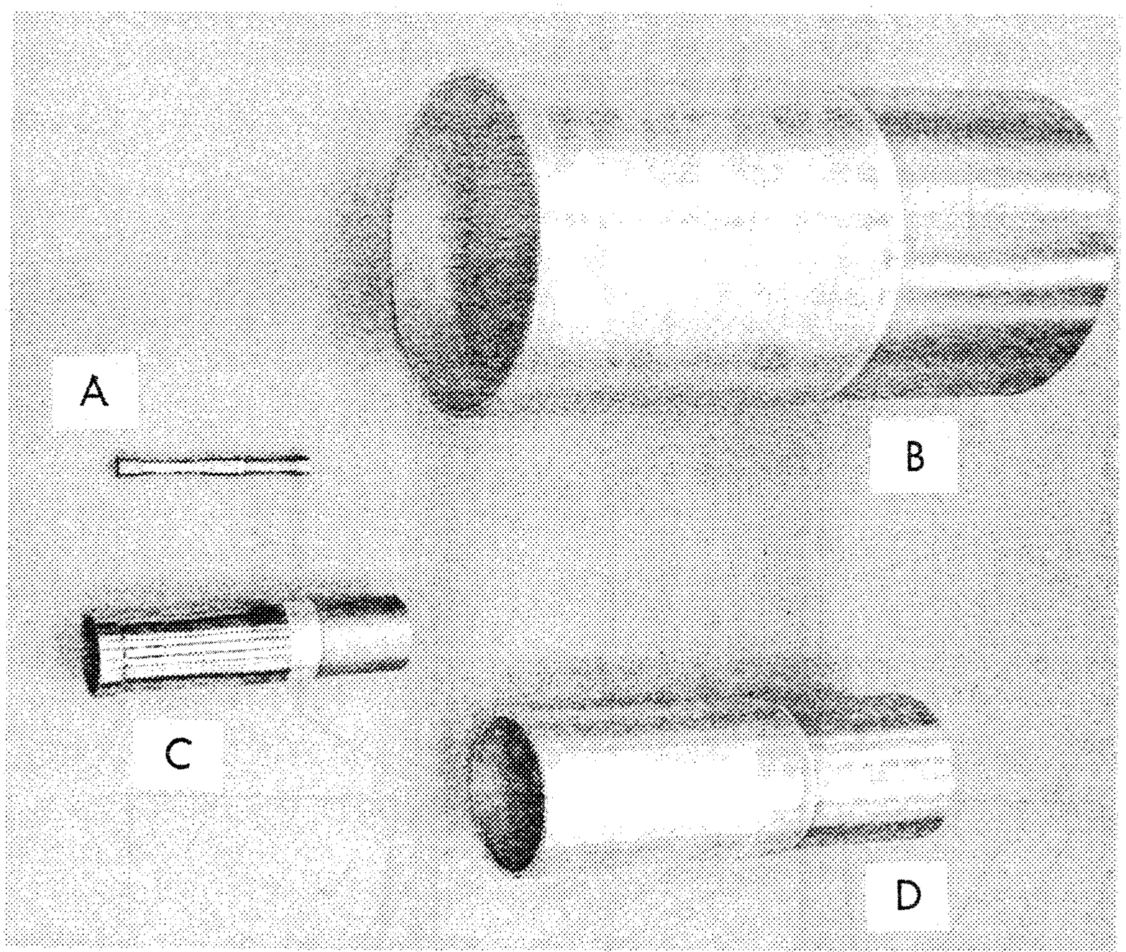
FIGURE 7 JOINT AND TOOLING ARRANGEMENT FOR DIFFUSION WELDING DISSIMILAR METAL TUBULAR ASSEMBLIES (0.50 Inch Dia.)



ASSEMBLY PROCEDURE

1. Assemble tubular joint to inner mandrel using shrink fit and cool to -320°F.
2. Heat outer ring to 500°F.
3. Insert tubular joint into outer die using arbor press.
4. Stabilize temperature of assembly prior to welding.

FIGURE 8 TOOLING ARRANGEMENT FOR WELDING DISSIMILAR METAL TUBULAR ASSEMBLIES (2.0, 4.0 and 8.0-Inch Diameter)



2X15491

A 0.50-Inch Diameter 2219 Aluminum Alloy to 321 Stainless Steel
B 8.0-Inch Diameter 2219 Aluminum Alloy to Ti-5Al-2.5Sn Alloy
C 2.0-Inch Diameter 321 Stainless Steel to Ti-8Al-1Mo-1V Alloy
D 4.0-Inch Diameter 2219 Aluminum Alloy to 321 Stainless Steel

FIGURE 9 APPEARANCE OF TUBULAR TRANSITION JOINTS AFTER DIFFUSION WELDING

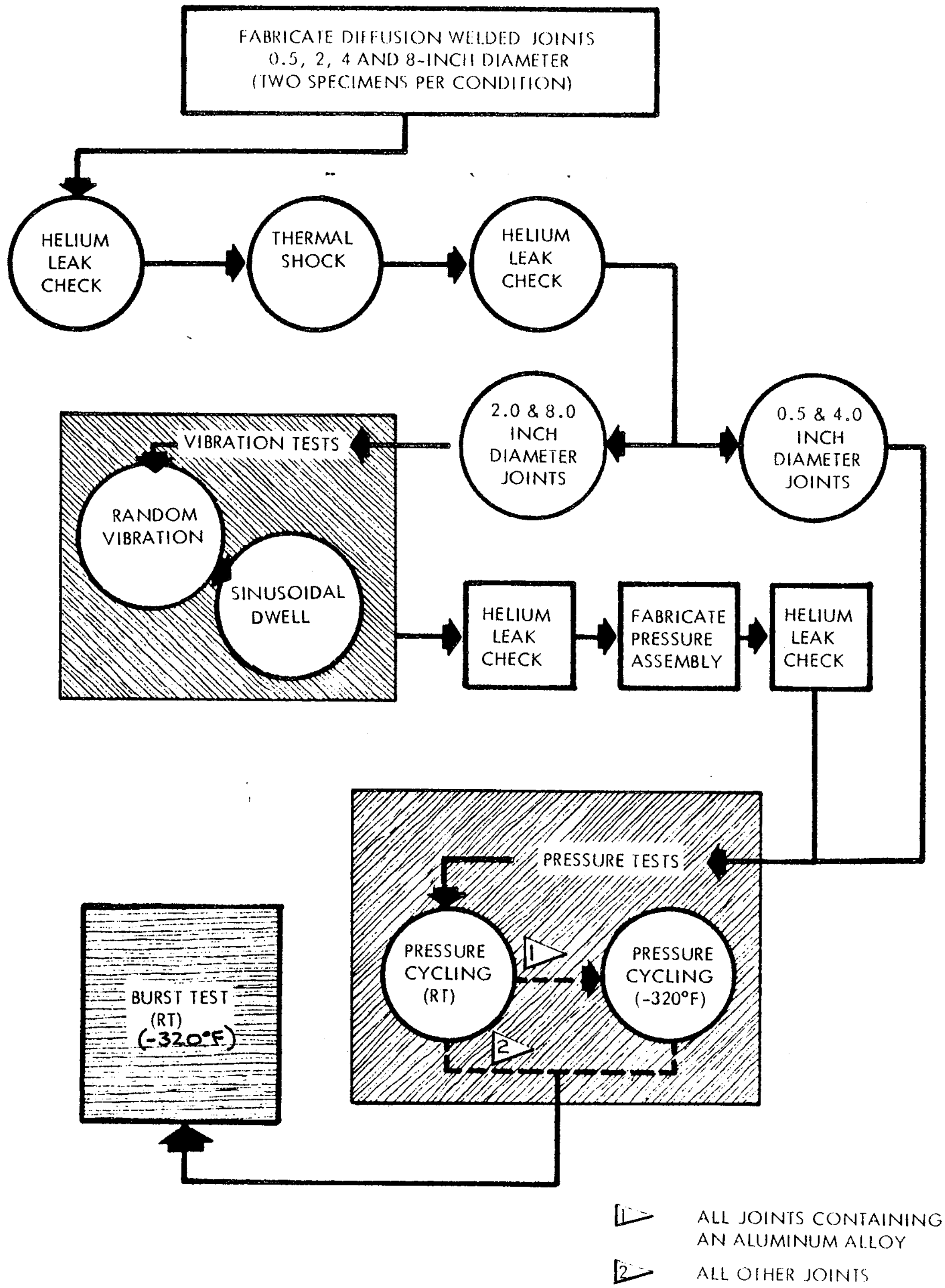
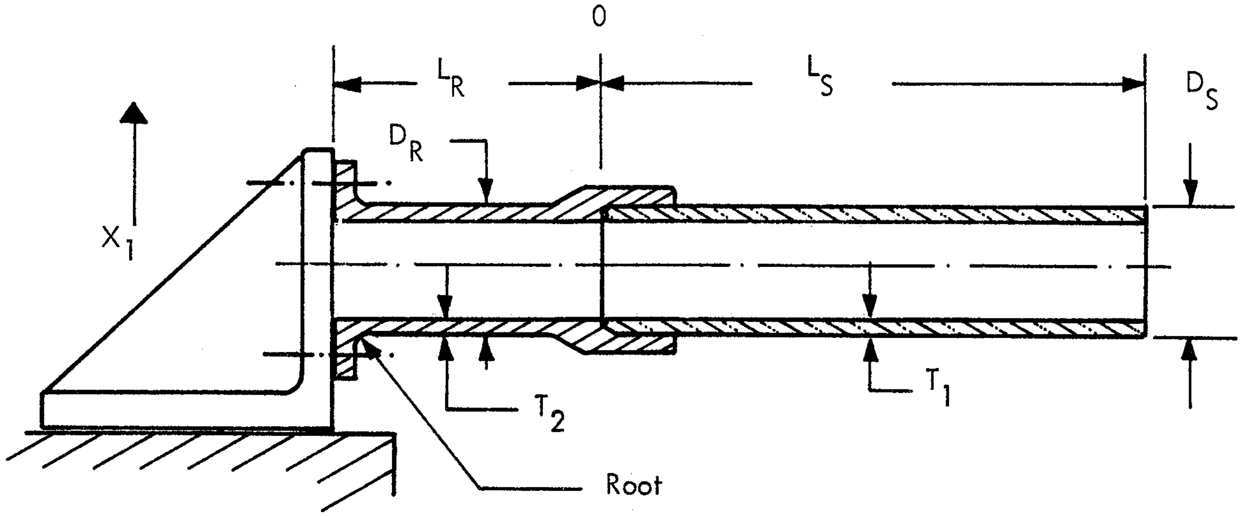


FIGURE 10 FLOW DIAGRAM OF SEQUENTIAL TESTING OF THE DIFFUSION WELDED JOINTS



TUBE DIMENSIONS

Joint Dia.	Outer Tube	Inner Tube	T_1 (in.)	T_2 (in.)	D_R (in.)	D_S (in.)	L_R (Ft.)	L_S (Ft.)
2.0	2219	321	.060	.100	2.080	2	.25	1.25
8.0	2219	321	.060	.100	8.080	8	1	2.0
2.0	2219	Ti-5Al-2.5Sn	.080	.100	2.080	2	.25	1.50
8.0	2219	Ti-5Al-2.5Sn	.080	.100	8.080	8	1	2.50
2.0	321	Ti-8Al-1Mo-1V	.060	.060	2.00	2	.25	1.50
8.0	321	Ti-8Al-1Mo-1V	.060	.080	8.040	8	1	2.50

FIGURE 11. VIBRATION TEST SPECIMEN CONFIGURATION

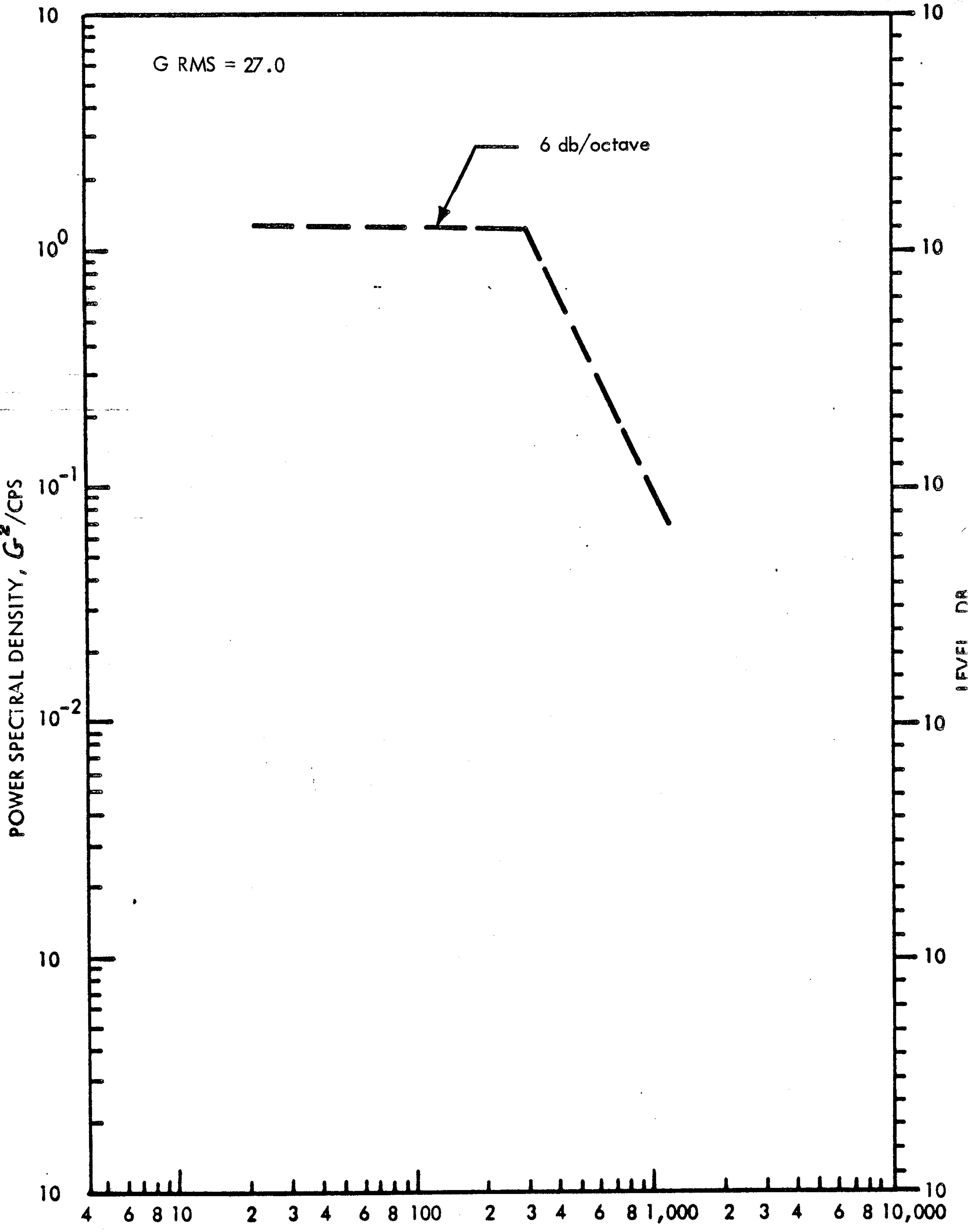
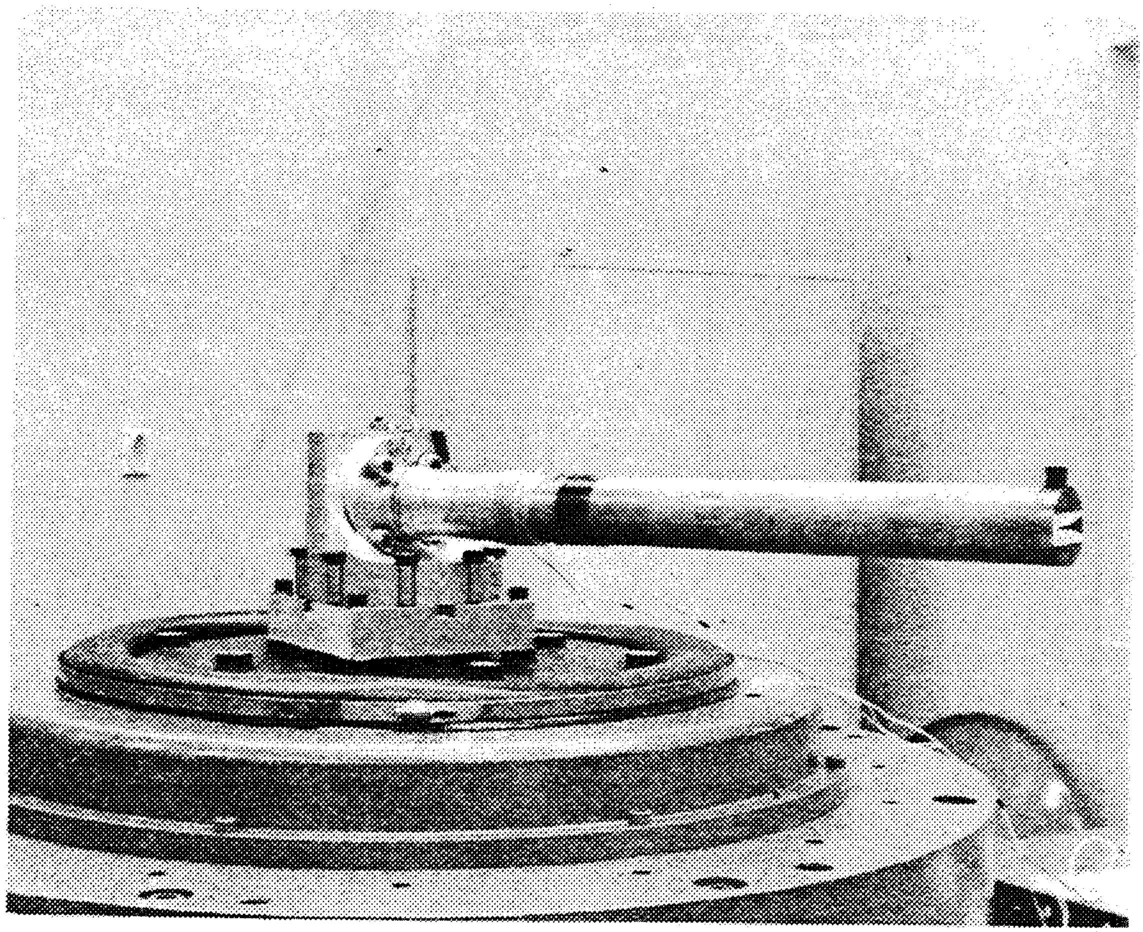


FIGURE 12 POWER SPECTRAL DENSITY VERSUS FREQUENCY TEST SPECIFICATION



SPECIMEN A6 2X15490

FIGURE 13 VIBRATION TEST ARRANGEMENT FOR 2.0-INCH DIAMETER JOINTS

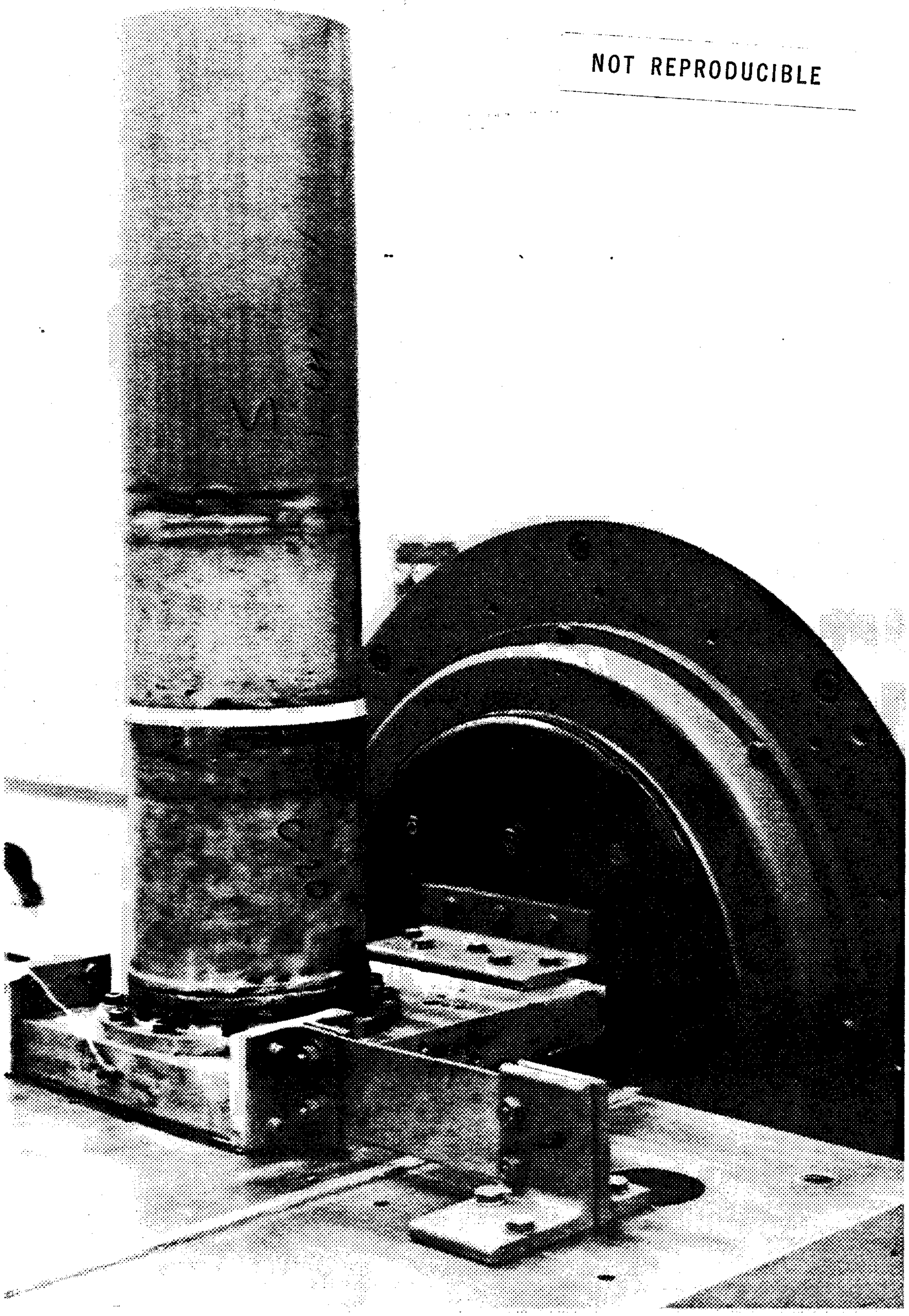
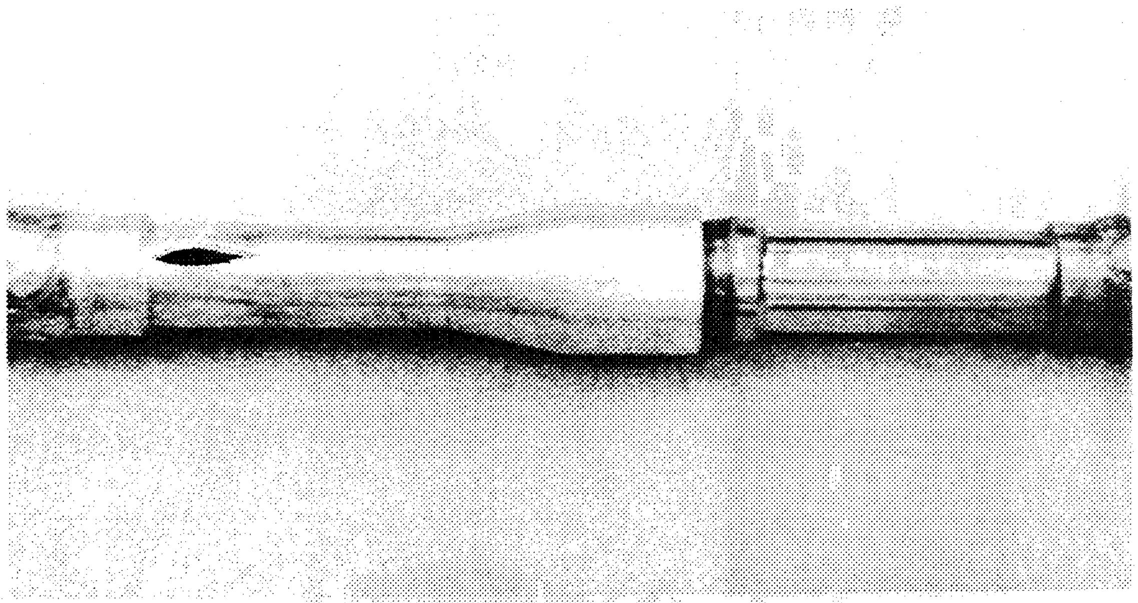
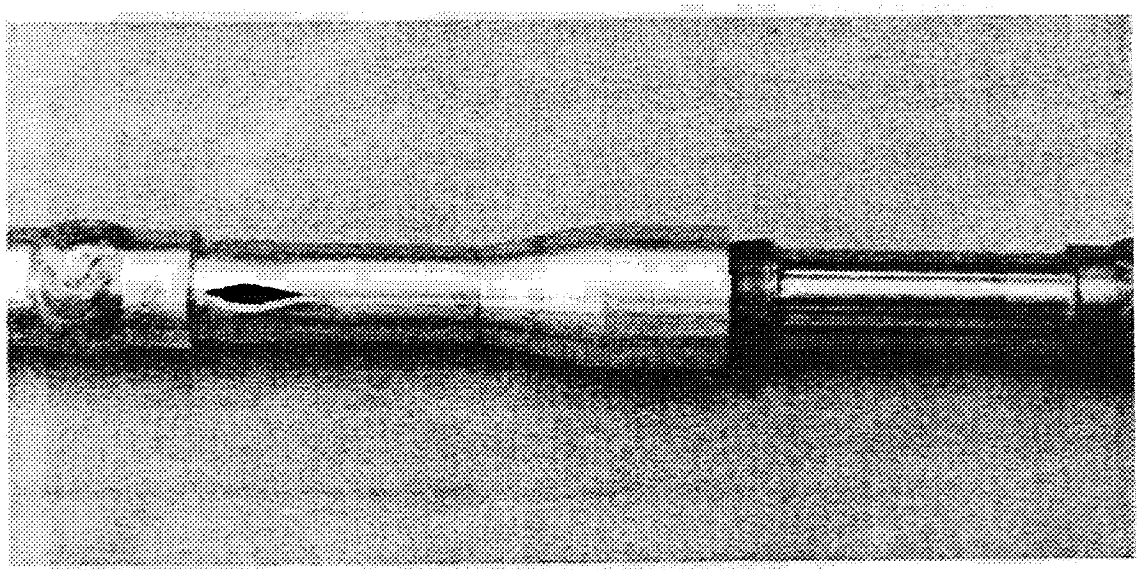


FIGURE 14 VIBRATION TEST ARRANGEMENT FOR 8.0-INCH DIAMETER JOINTS



SPECIMEN A1
R.T. BURST PRESSURE - 8100 PSIG

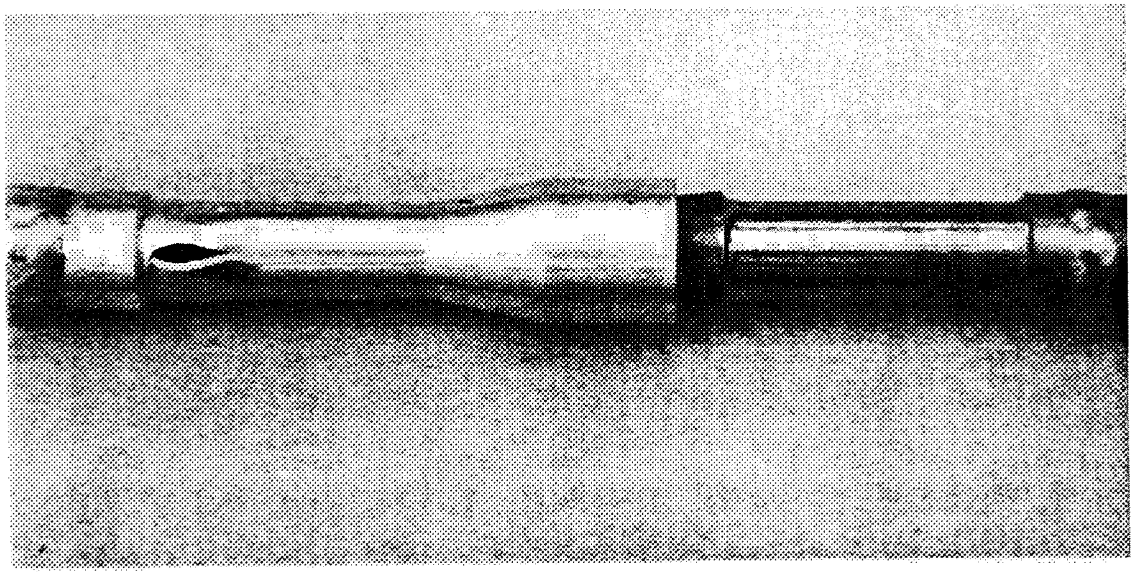
2A253115



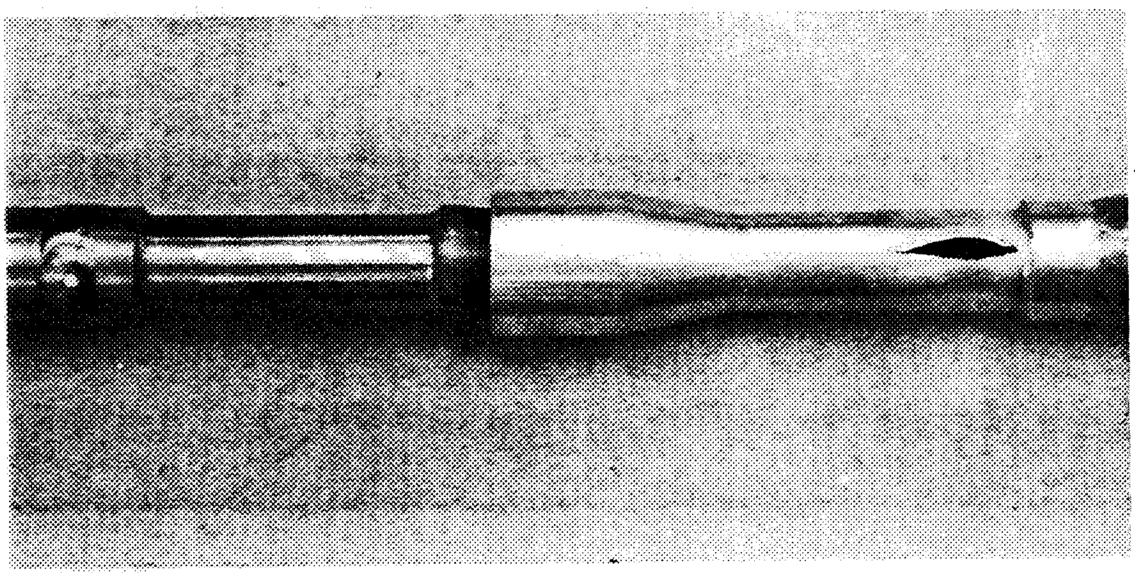
SPECIMEN A2
R.T. BURST PRESSURE - 6600 PSIG

2A253116

FIGURE 15 0.50-INCH DIAMETER JOINTS AFTER BURST TEST (2219 Al TO 321 SS)

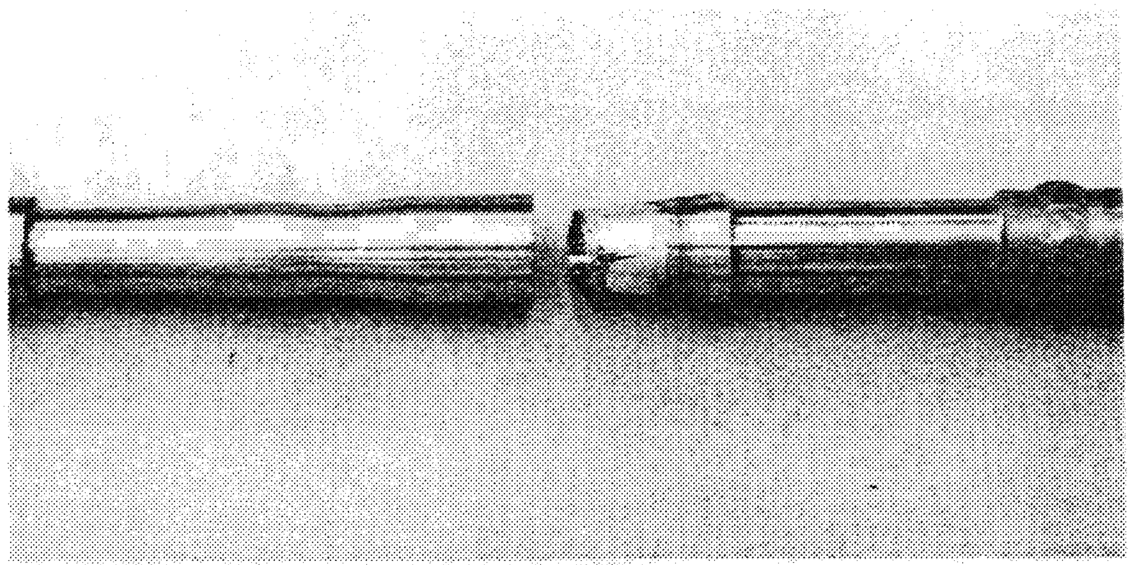


SPECIMEN B1 2A253117
R.T. BURST PRESSURE - 7700 PSIG

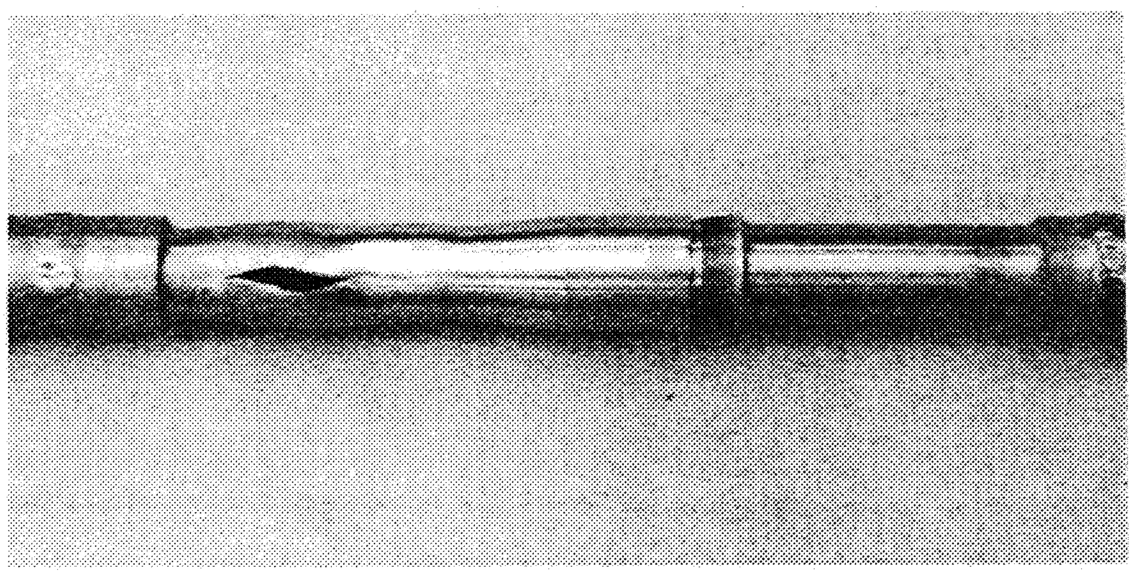


SPECIMEN B2 2A253118
R.T. BURST PRESSURE - 8300 PSIG

FIGURE 16 0.50-INCH DIAMETER JOINTS AFTER BURST TEST (2219 Al TO Ti-5Al-25Sn)

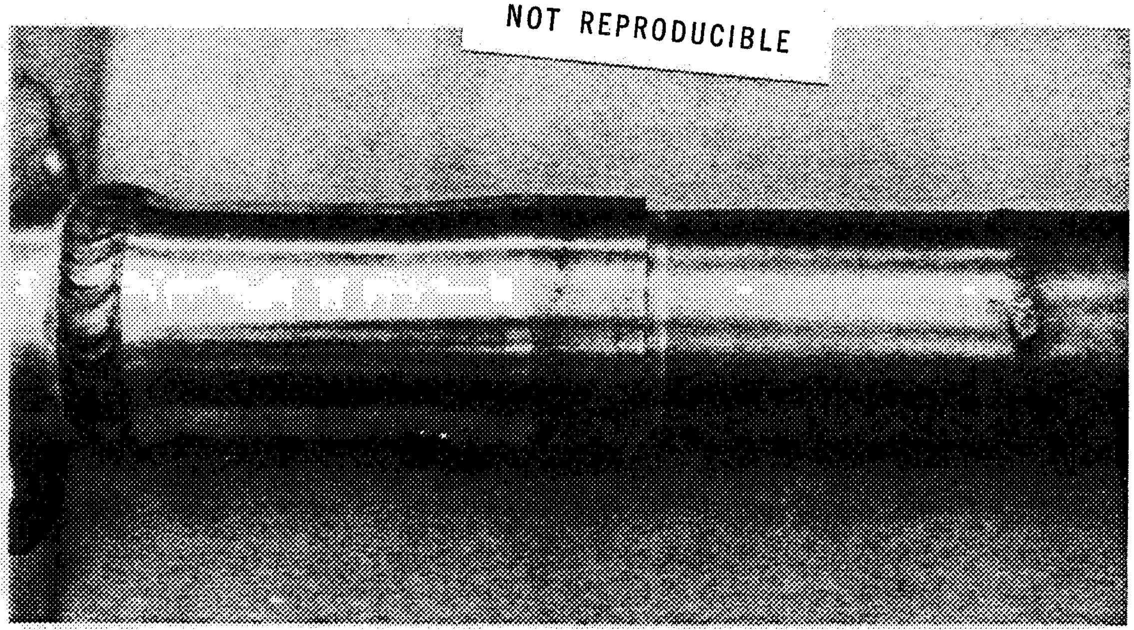


SPECIMEN C 1 2A253119
R.T. BURST PRESSURE - 11,600 PSIG

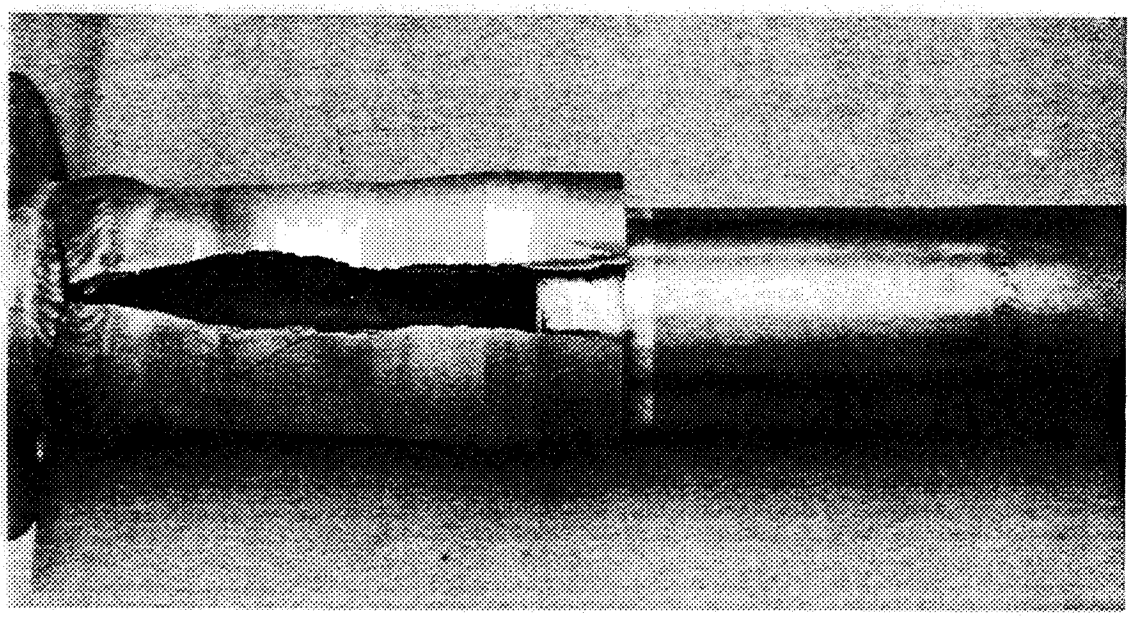


SPECIMEN C 2 2A253120
R.T. BURST PRESSURE - 12,200 PSIG

FIGURE 17 0.50-INCH DIAMETER JOINTS AFTER BURST TEST
(321 SS To Ti-8Al-1Mo-1V)

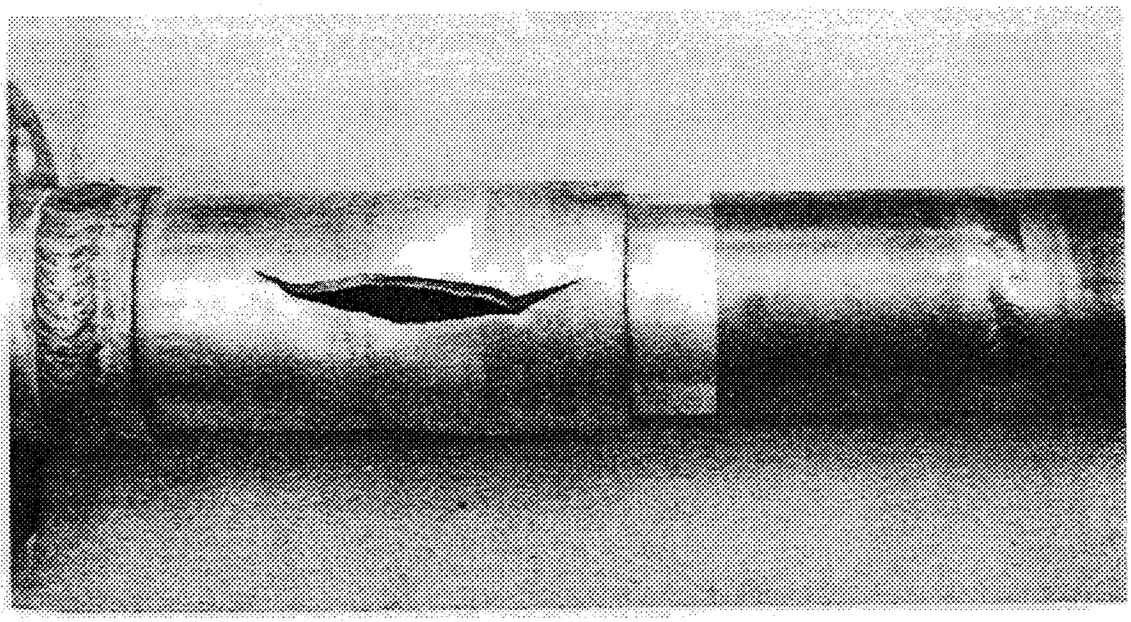


SPECIMEN A 8 2A253121
R.T. BURST PRESSURE - 4400 PSIG

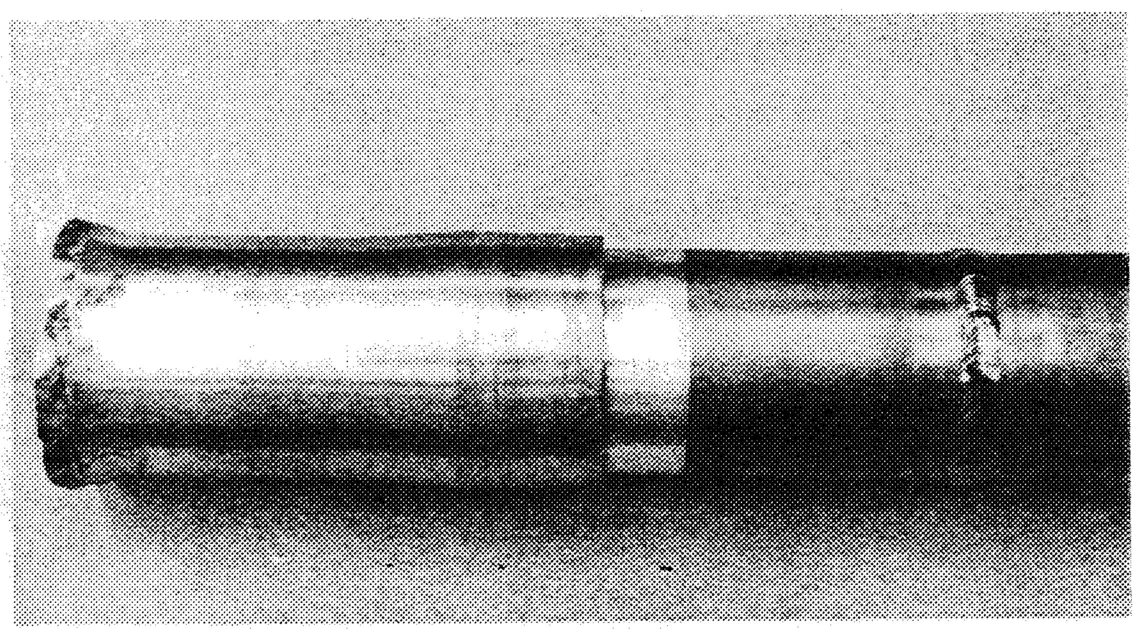


SPECIMEN A9 2A253122
-320°F BURST PRESSURE - 6150 PSIG

FIGURE 18 2.0-INCH DIAMETER JOINT AFTER BURST TEST (2219 Al TO 321 SS)

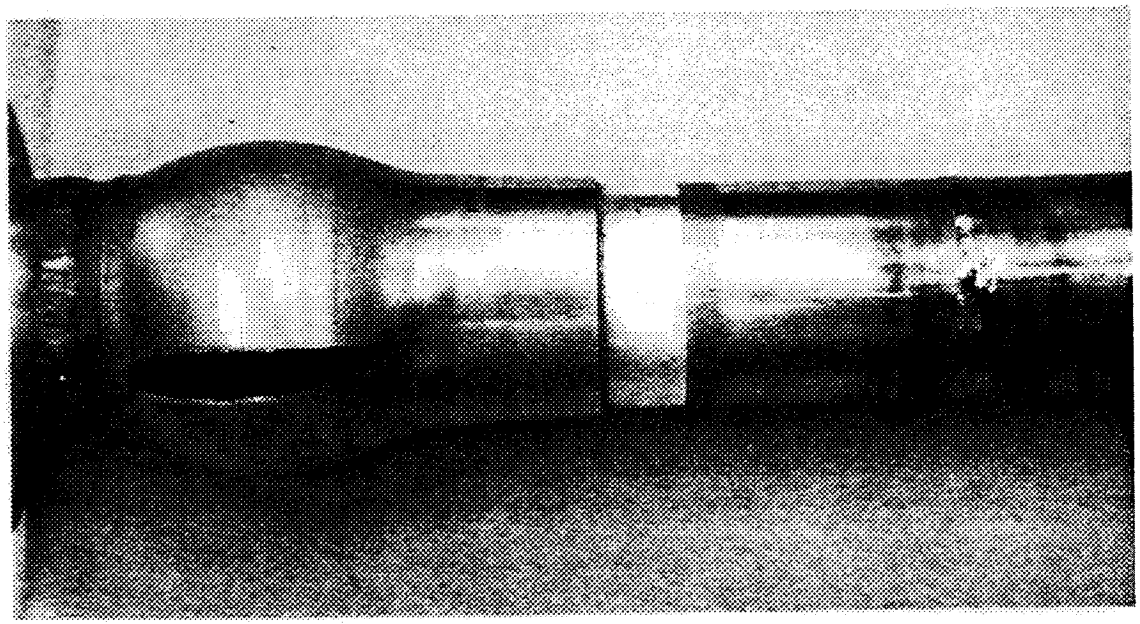


SPECIMEN B7 2A253123
R.T. BURST PRESSURE - 3800 PSIG



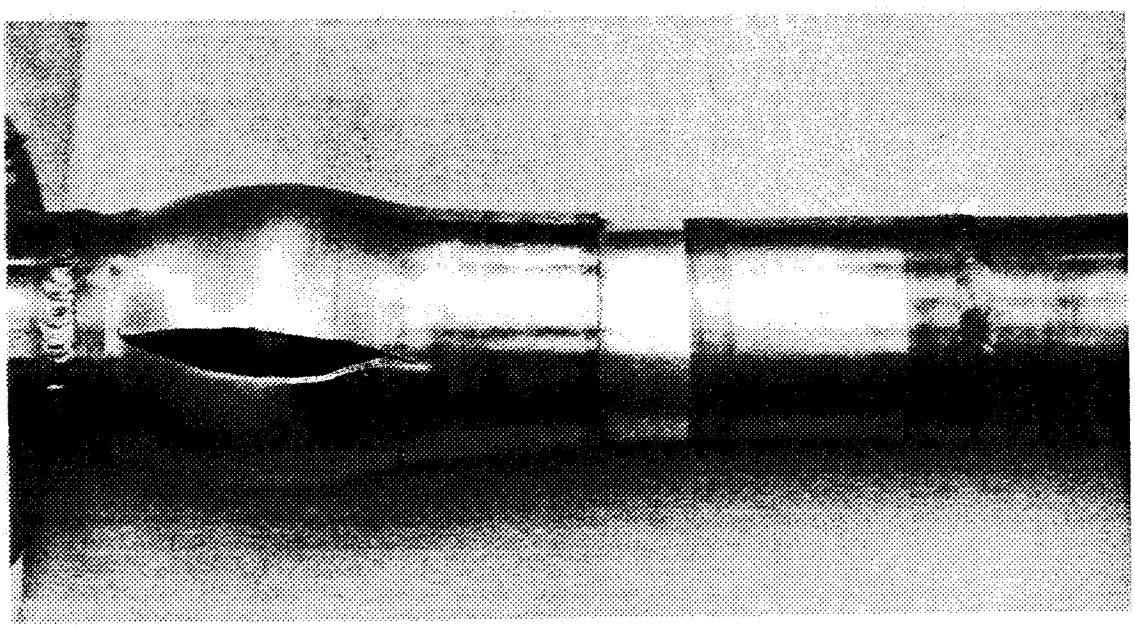
SPECIMEN B8 2A253124
-320°F BURST PRESSURE - 4460 PSIG

FIGURE 19 2.0-INCH DIAMETER JOINT AFTER BURST TEST
(2219 Al TO Ti-5Al-2.5Sn)



2A253125

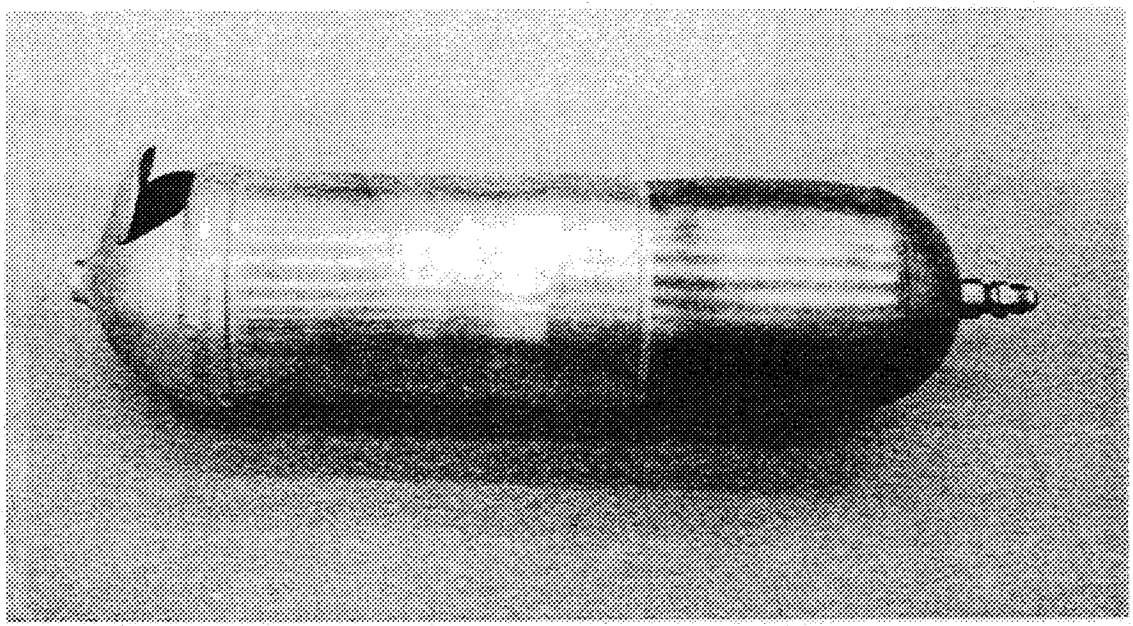
SPECIMEN C6
R.T. BURST PRESSURE - 5900 PSIG



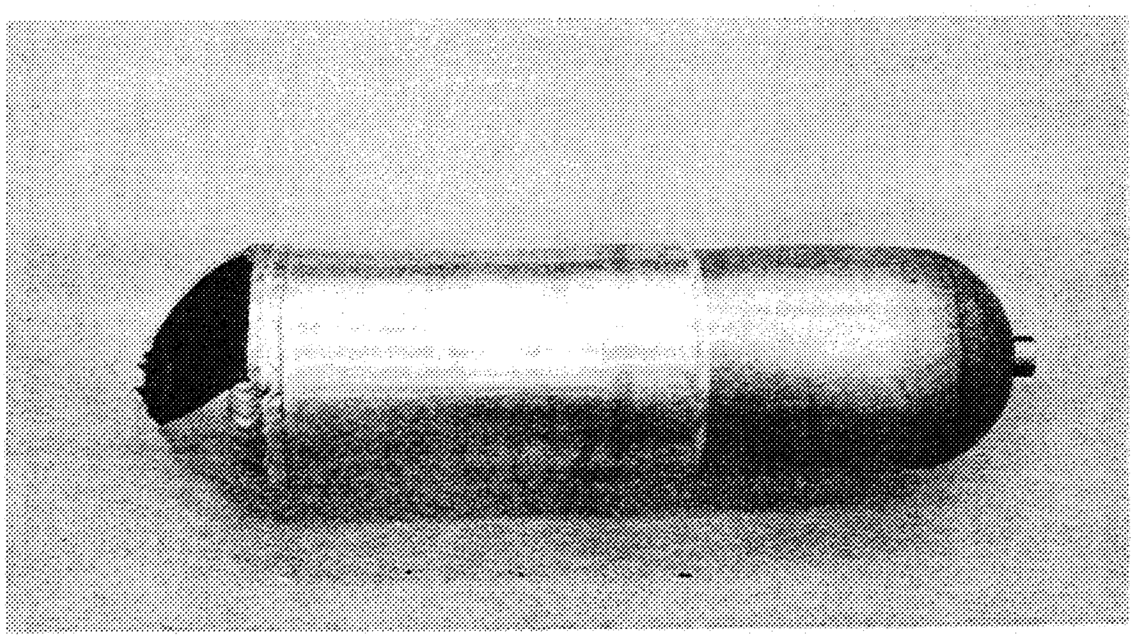
2A253126

SPECIMEN C7
R.T. BURST PRESSURE - 6150 PSIG

FIGURE 20 2.0-INCH DIAMETER JOINT AFTER BURST TEST (321 SS TO Ti-8Al-1Mo-1V)

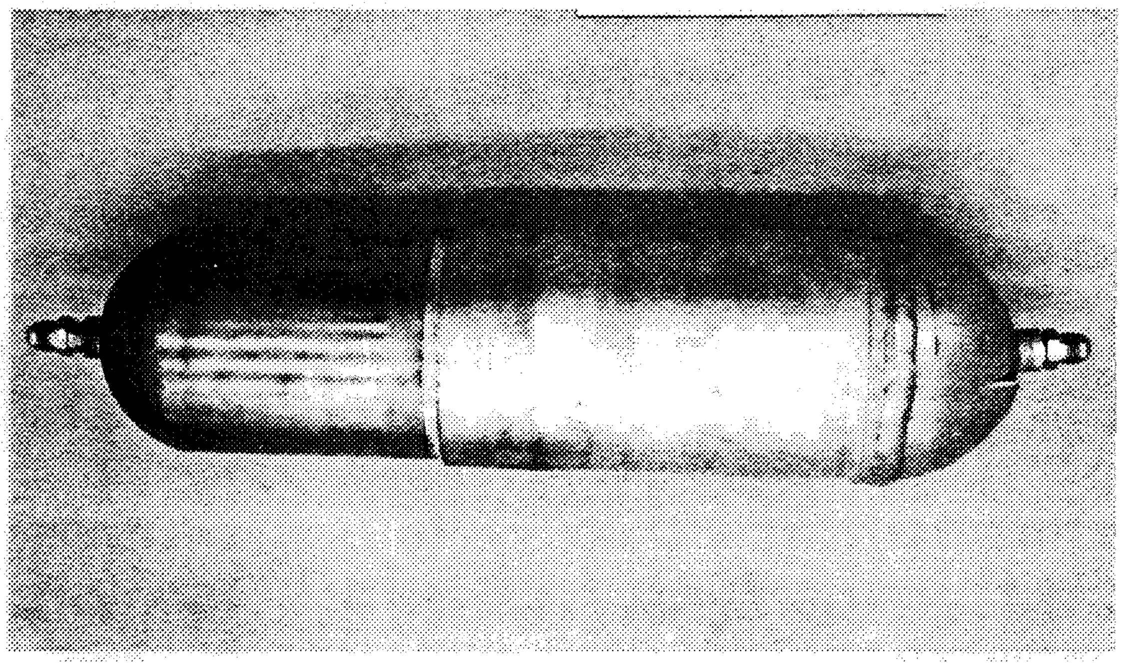


SPECIMEN A14 2A253127
R.T. BURST PRESSURE



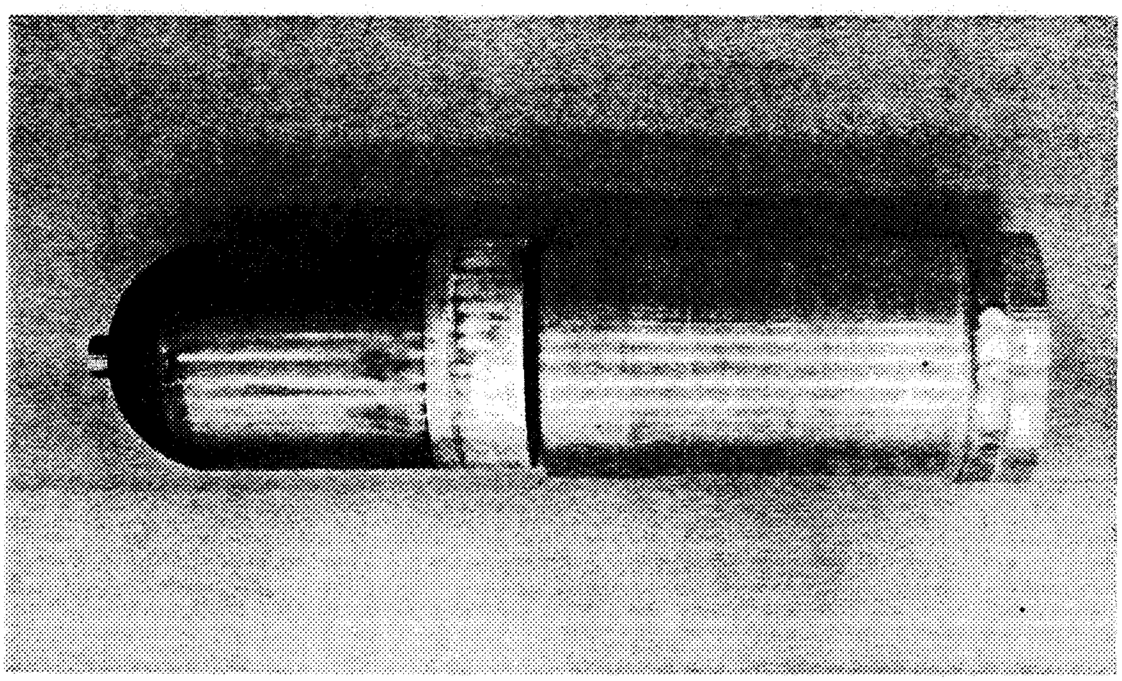
SPECIMEN A15 2A253128
-320°F BURST PRESSURE - 2550 PSIG

FIGURE 21 4.0-INCH DIAMETER JOINTS AFTER BURST TEST
(2219 Al to 321 SS)



SPECIMEN B14 2A253130

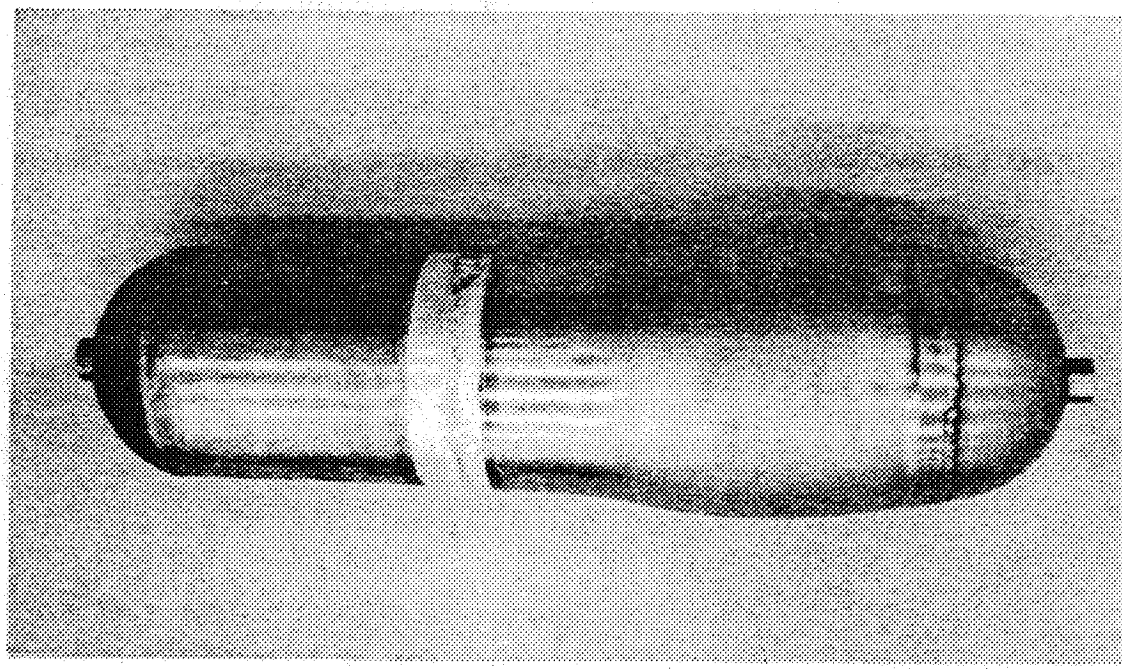
R.T. BURST PRESSURE - 1875 PSIG



SPECIMEN B-15 2A253129

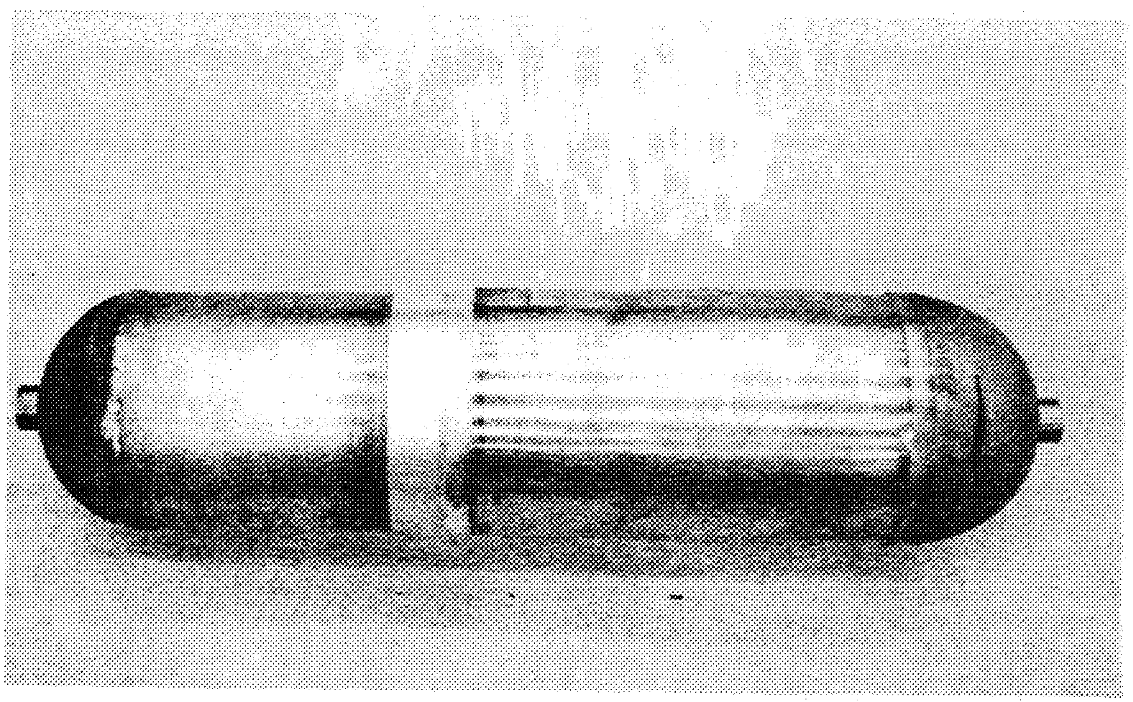
-320°F BURST PRESSURE - 1600 PSIG

FIGURE 22 4.0-INCH DIAMETER JOINTS AFTER BURST TEST (2219 Al TO Ti-5Al-2.5Sn)



SPECIMEN C14
R.T. BURST PRESSURE - 3020 PSIG

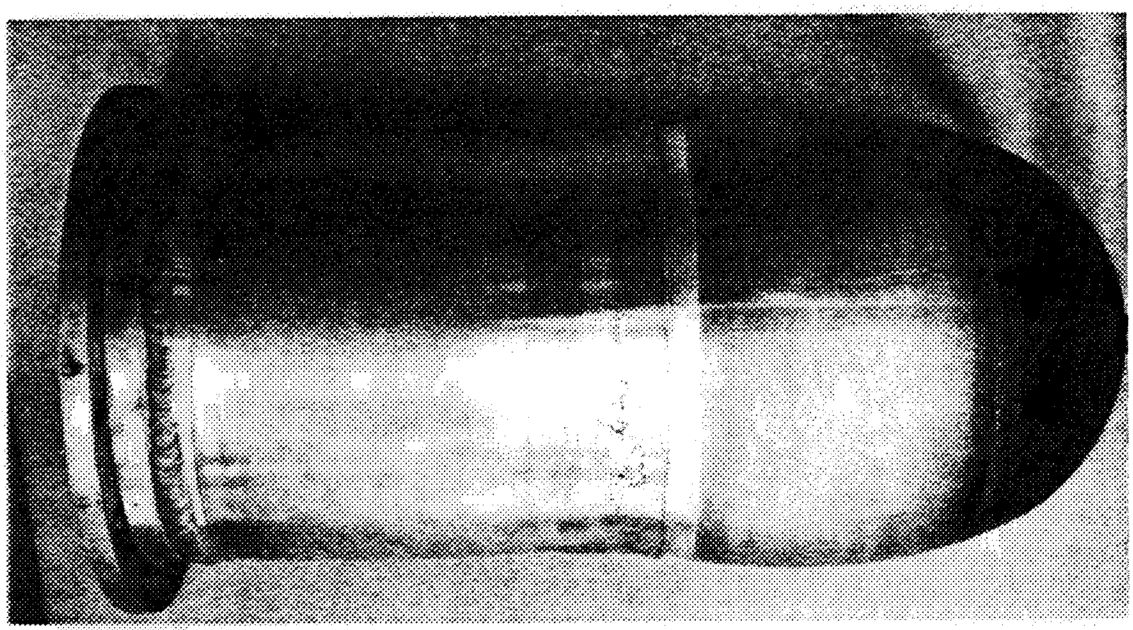
2A253131



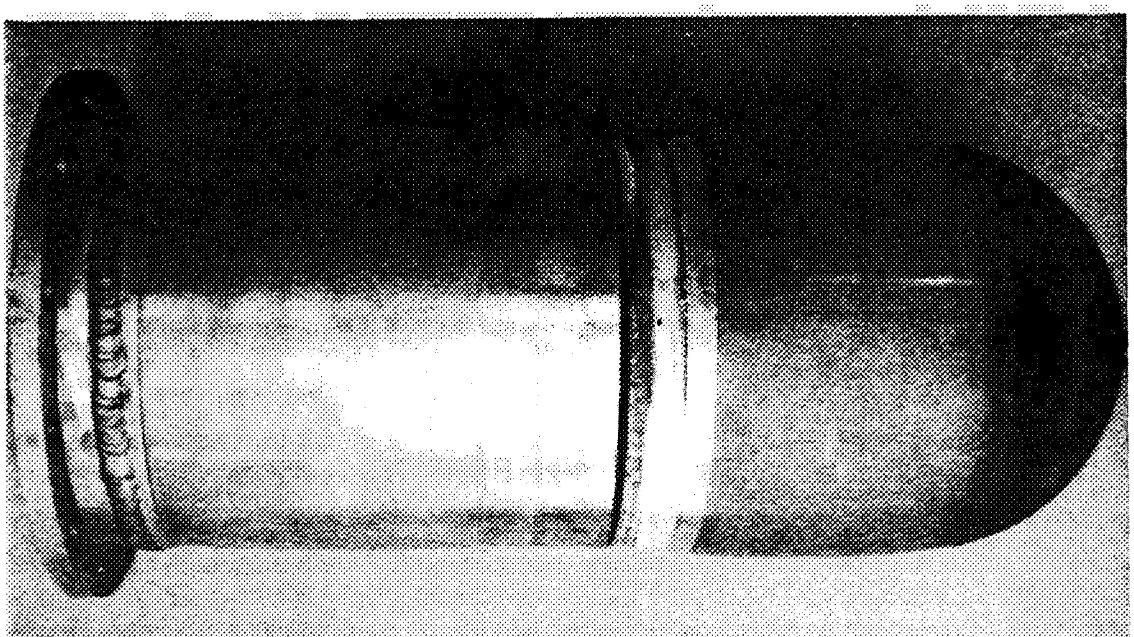
SPECIMEN C15
-320°F BURST PRESSURE - 4120 PSIG

2A253132

FIGURE 23 4.0-INCH DIAMETER JOINTS AFTER BURST TEST (321 SS TO Ti-8Al-1Mo-1V)

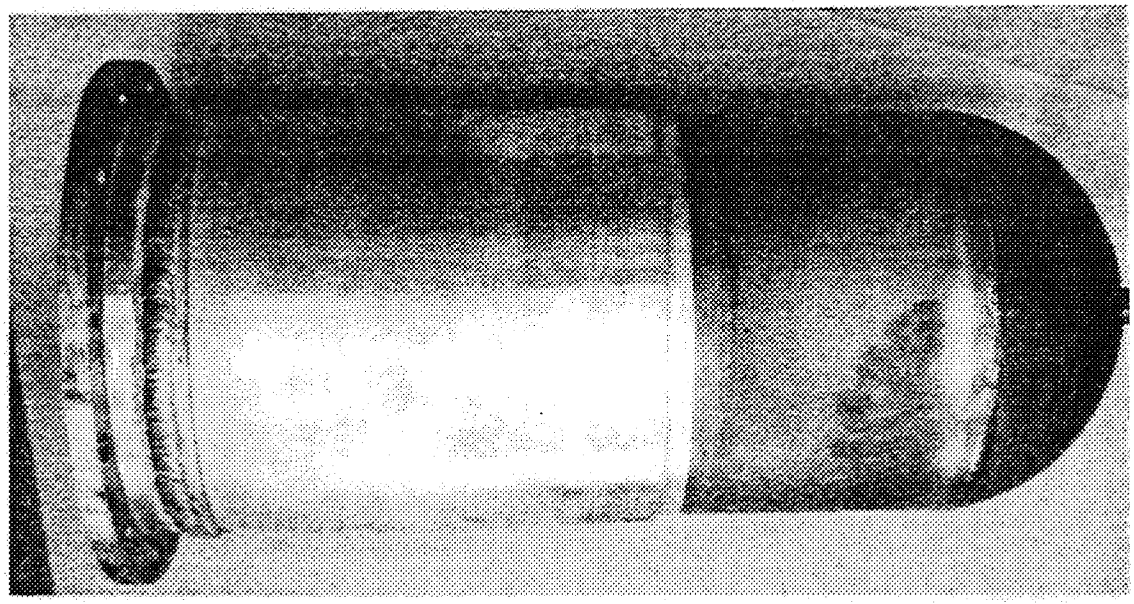


SPECIMEN A19 2A253133
R.T. BURST PRESSURE - 1375 PSIG

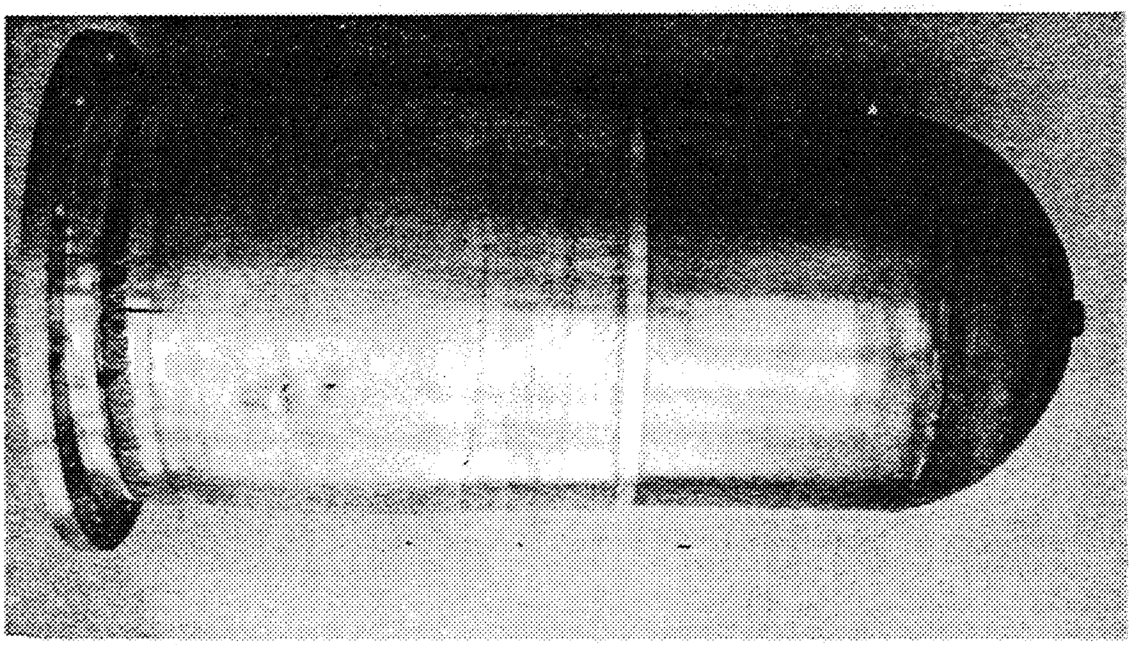


SPECIMEN A20 2A253134
-320°F BURST PRESSURE - 1620 PSIG

FIGURE 24 8.0-INCH DIAMETER JOINTS AFTER BURST TEST (2219 Al to 321 SS)

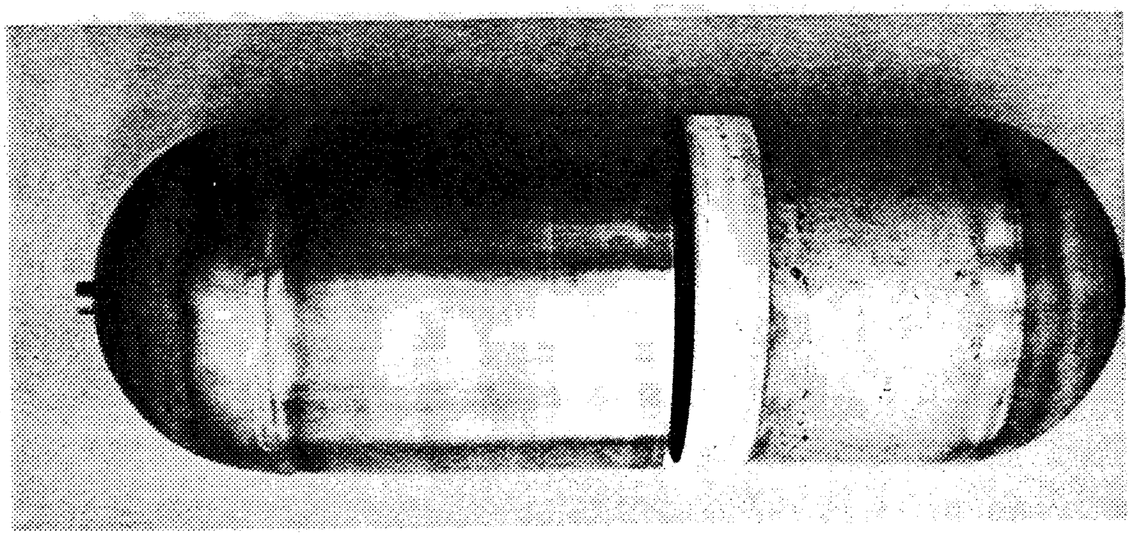


SPECIMEN B19 2A253135
R.T. BURST PRESSURE - 1100 PSIG



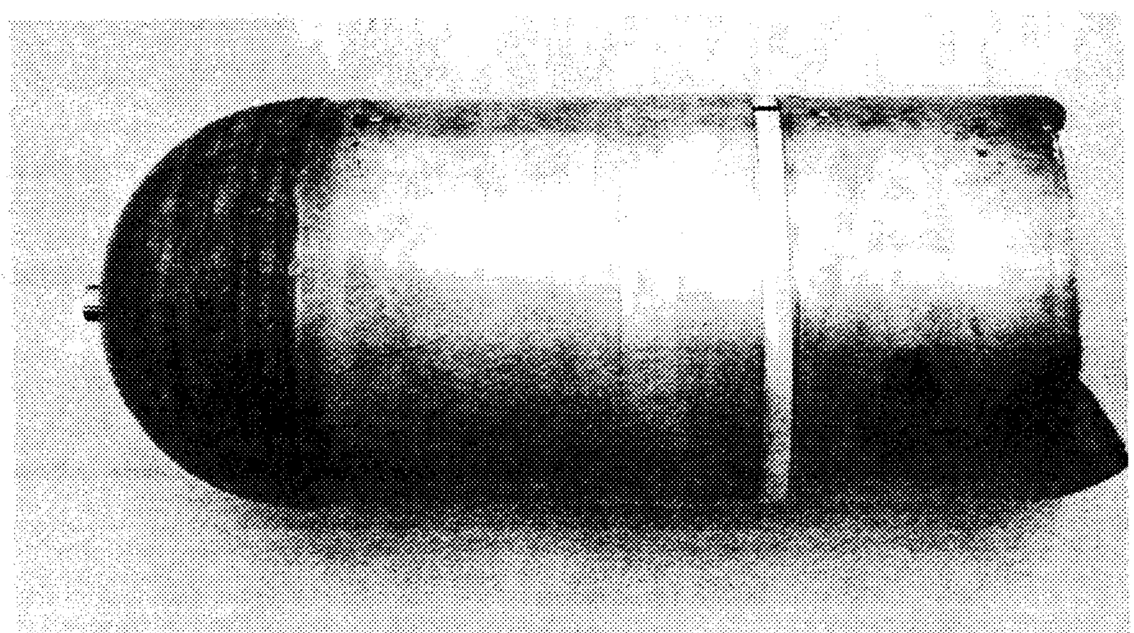
SPECIMEN B20 2A253136
-320°F BURST PRESSURE - 1408 PSIG

FIGURE 25 8.0-INCH DIAMETER JOINTS AFTER BURST TEST (2219 Al TO Ti-5Al-2.5Sn)



SPECIMEN C19
R.T. BURST PRESSURE - 1245 PSIG

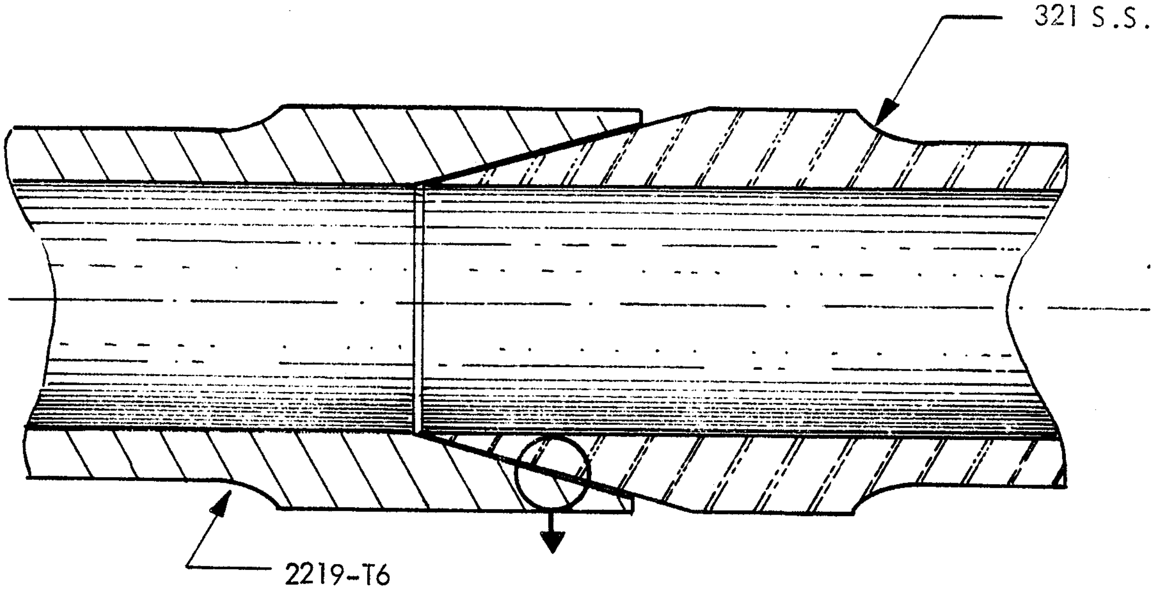
2A253137

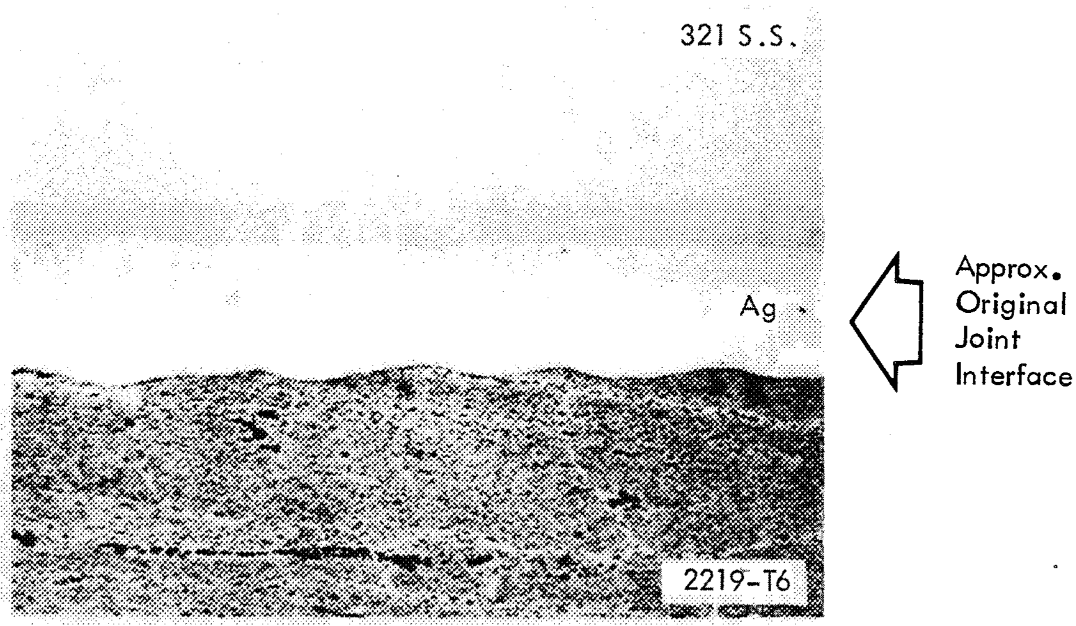


SPECIMEN C20
-320°F BURST PRESSURE - 890 PSIG

2A253138

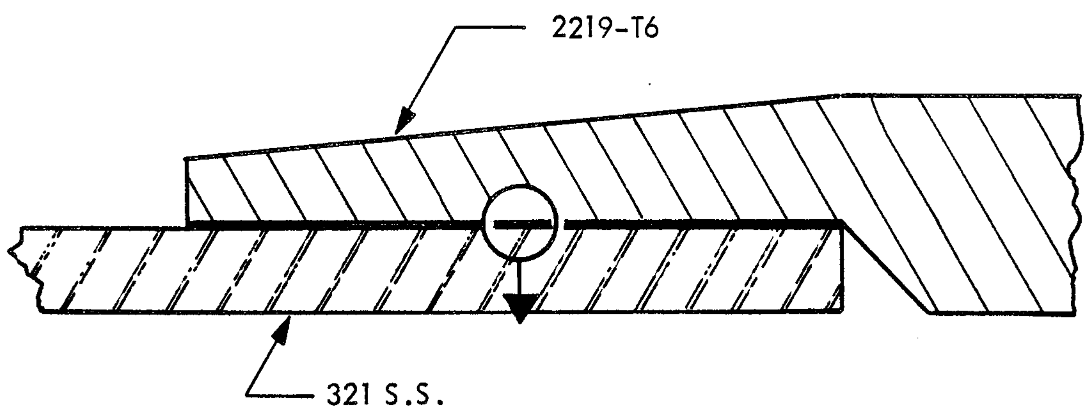
FIGURE 26 8.0-INCH DIAMETER JOINTS AFTER BURST TEST (321 SS TO Ti-8Al-1Mo-1V)

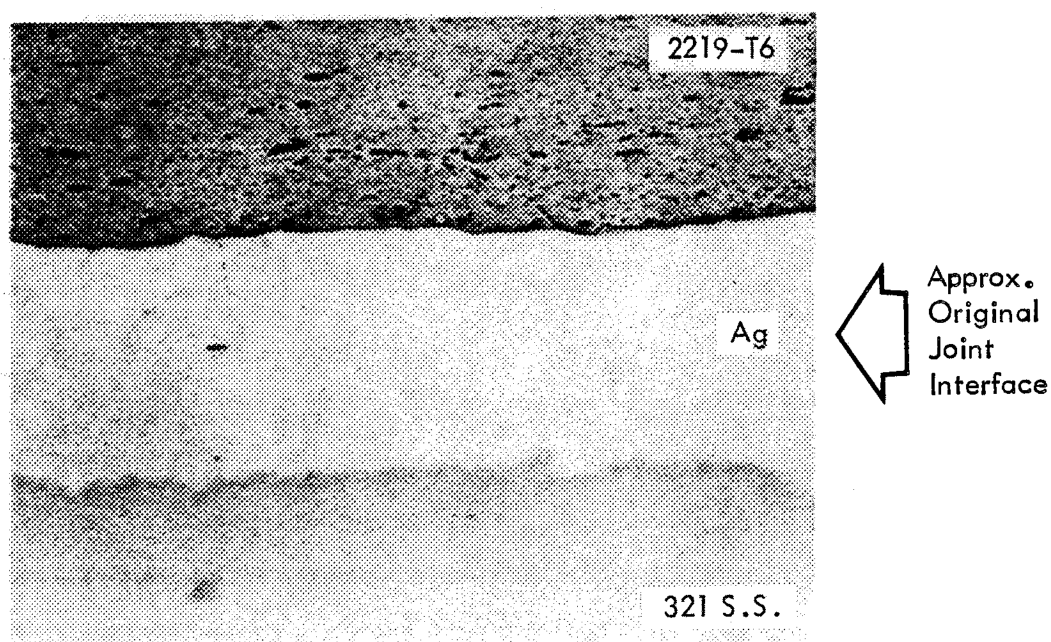




750X ETCHED - 2A253171
500°F for 2 Hours

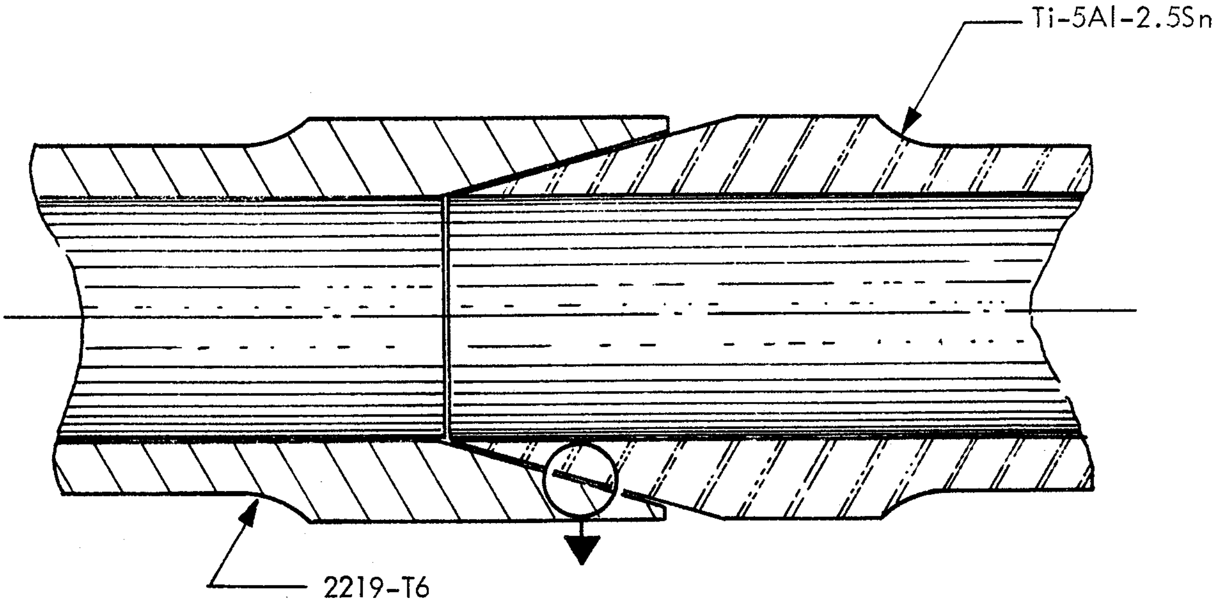
FIGURE 27 TYPICAL MICROSTRUCTURE OF 2219-T6 ALUMINUM ALLOY TO AISI TYPE 321 STAINLESS STEEL DIFFUSION WELD - FROM 0.50-INCH DIAMETER TUBULAR JOINT

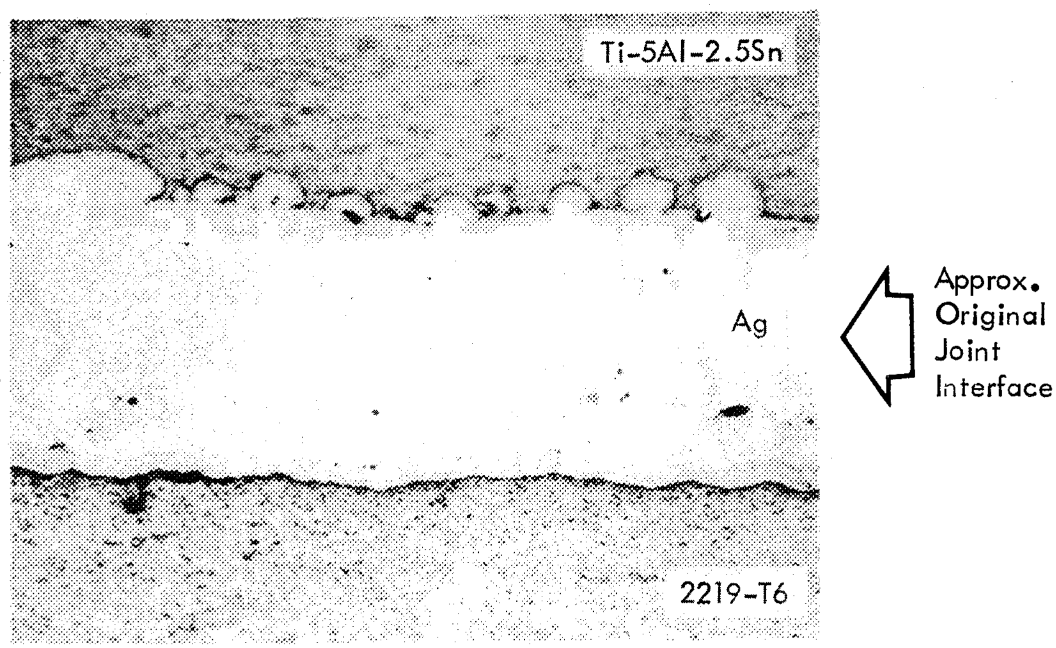




750X ETCHED 2A253172
500°F for 2 Hours

FIGURE 28 TYPICAL MICROSTRUCTURE OF 2219-T6 ALUMINUM ALLOY TO AISI TYPE 321 STAINLESS STEEL DIFFUSION WELD - FROM 2.0-INCH DIAMETER TUBULAR JOINT



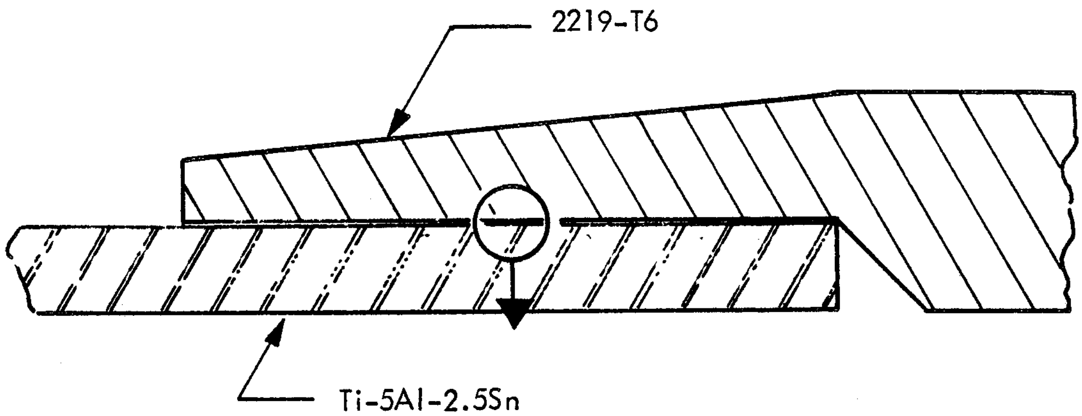


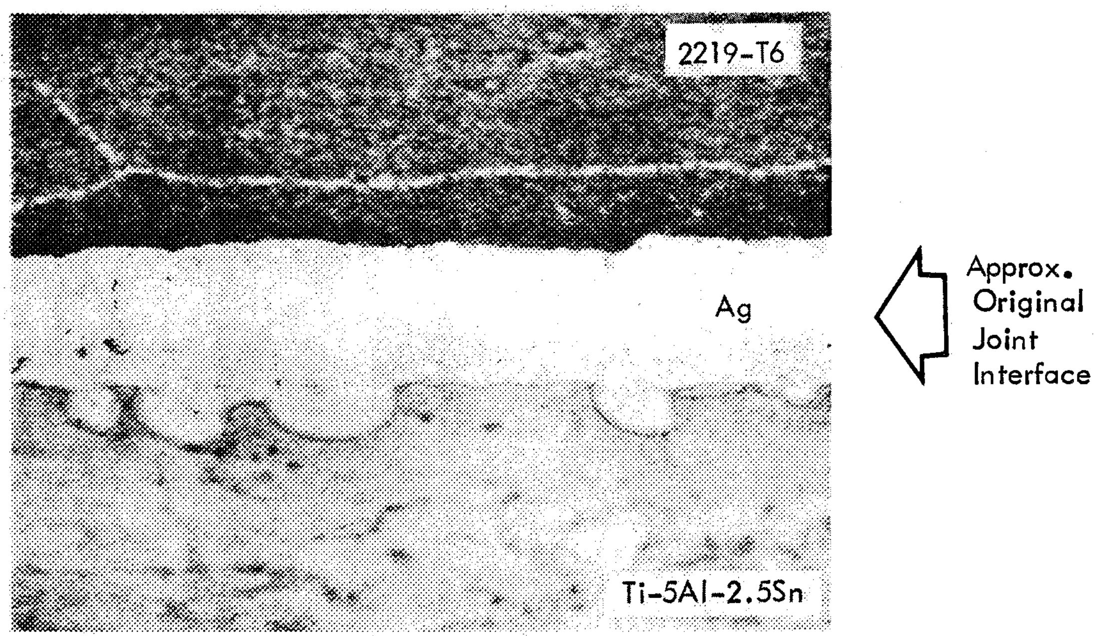
750X ETCHED 2A253174

600°F for 1 Hour

(Ag Electroplate Prediffused on Ti at 1300°F for 1 Hr.)

FIGURE 29 TYPICAL MICROSTRUCTURE OF 2219-T6 ALUMINUM ALLOY TO Ti-5Al-2.5Sn TITANIUM ALLOY DIFFUSION WELD - FROM 0.5-INCH DIAMETER TUBULAR JOINT

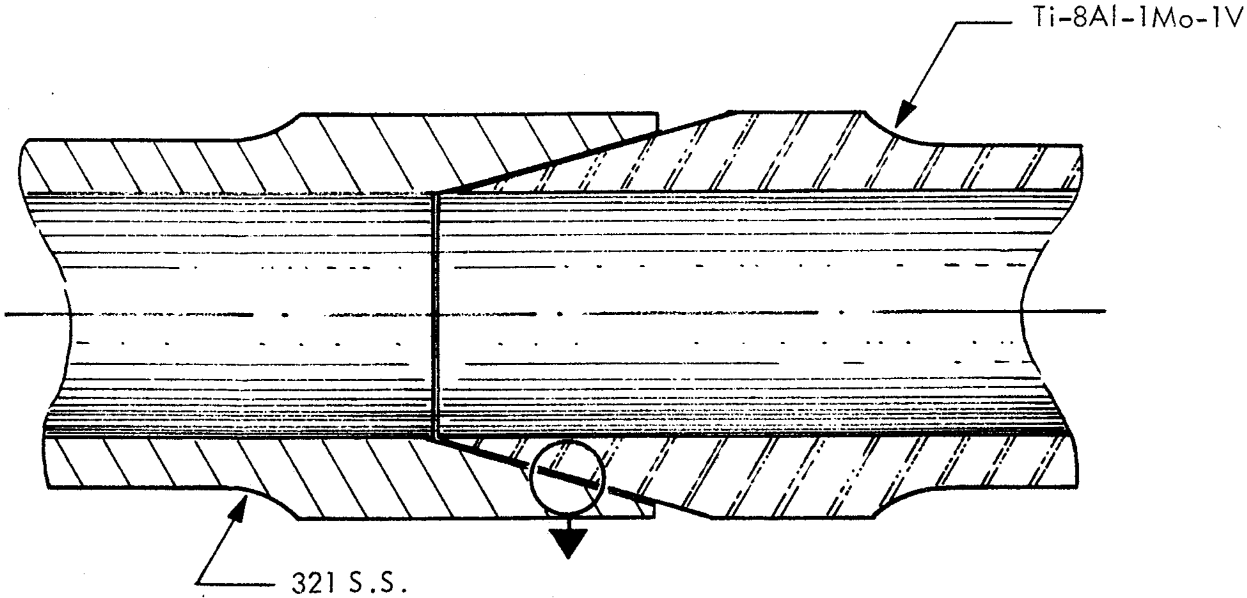


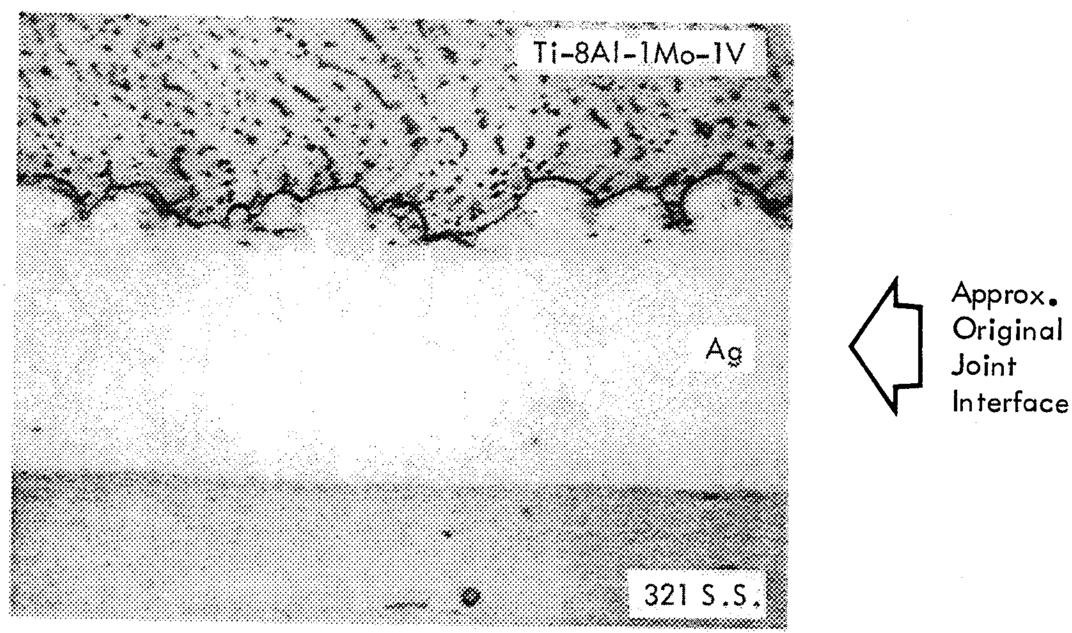


750X ETCHED 2A253175
600°F for 1 Hour

(Ag Electroplate Prediffused on Ti at 1300°F for 1 Hr.)

FIGURE 30 TYPICAL MICROSTRUCTURE OF 2219-T6 ALUMINUM ALLOY TO Ti-5Al-2.5Sn TITANIUM ALLOY DIFFUSION WELD - FROM 2.0-INCH DIAMETER TUBULAR JOINT

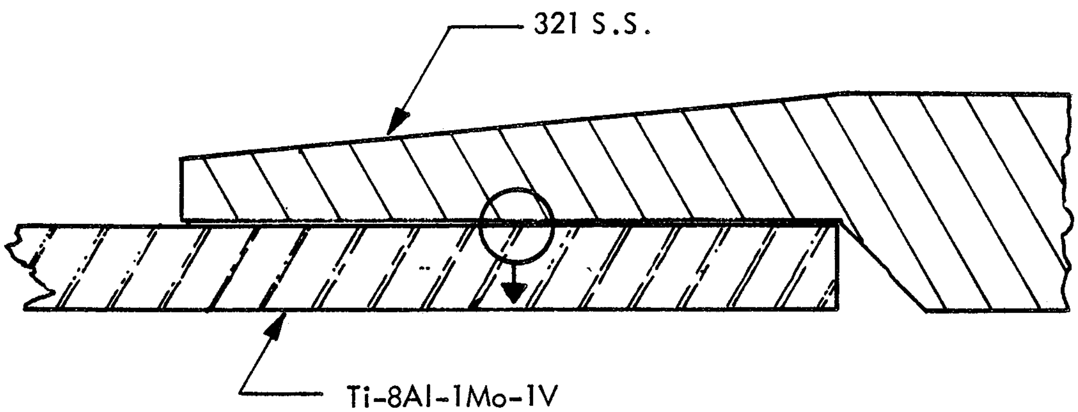


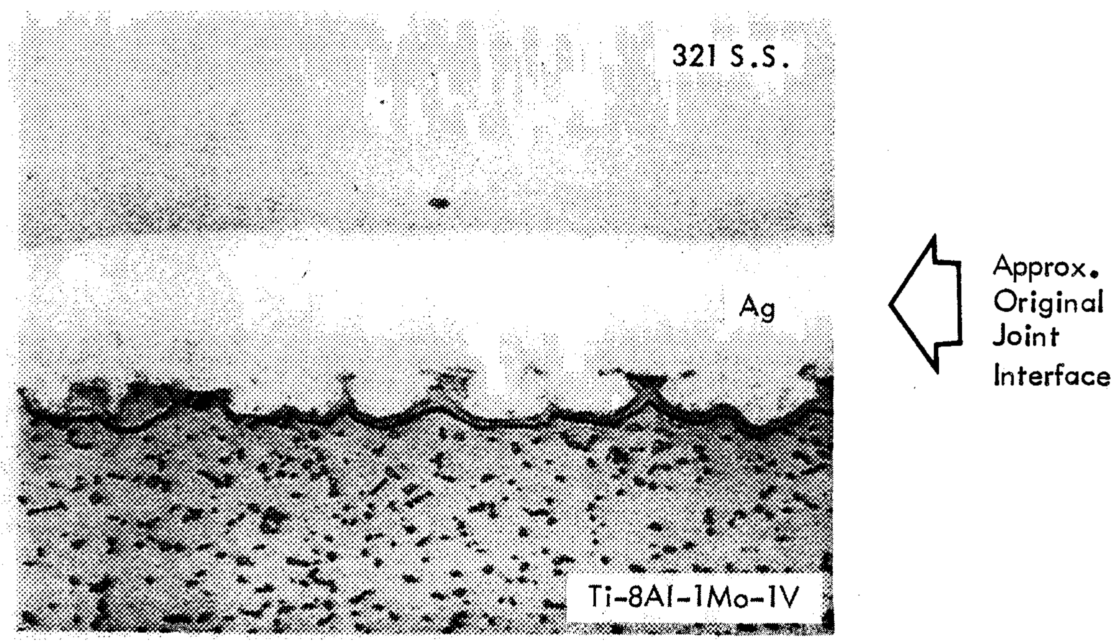


750X 2A253180

ETCHED
700°F for 30 Minutes
(Ag Electroplate Prediffused on Ti at 1300°F for 1 Hr.)

FIGURE 31 TYPICAL MICROSTRUCTURE OF AISI TYPE 321 STAINLESS STEEL TO Ti-8Al-1Mo-1V TITANIUM ALLOY DIFFUSION WELD - FROM 0.5-INCH DIAMETER TUBULAR JOINT





750X

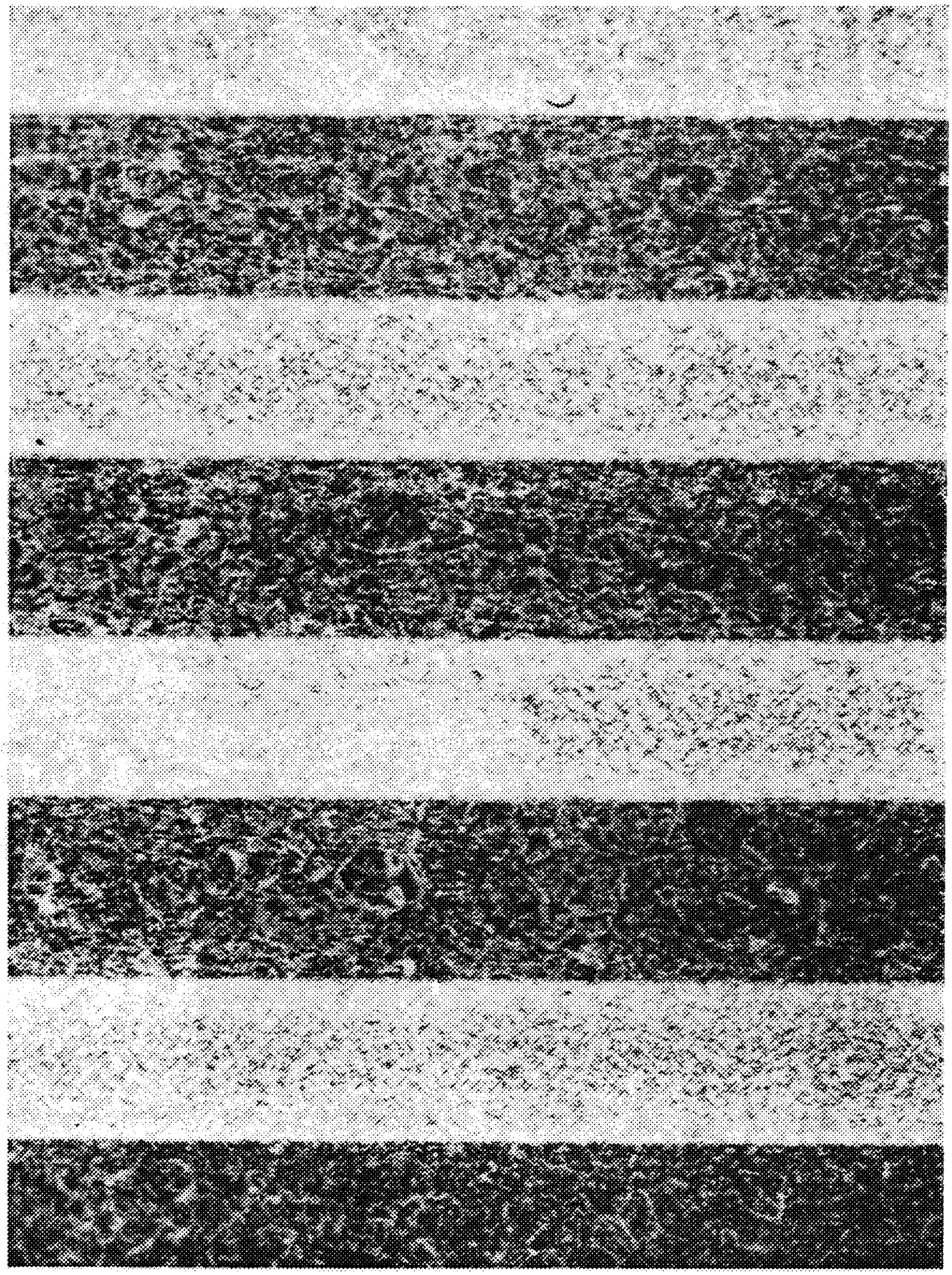
2A253173

ETCHED

700°F for 30 Minutes

(Ag Electroplate Prediffused on Ti at 1300°F for 1 Hr.)

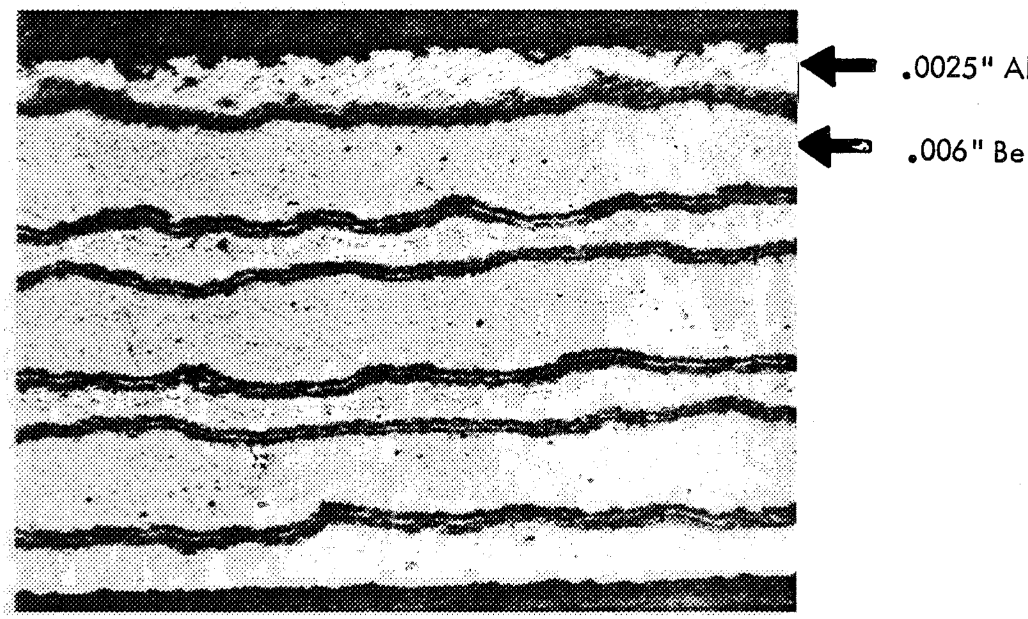
FIGURE 32 TYPICAL MICROSTRUCTURE OF AISI TYPE 321 STAINLESS STEEL to Ti-8Al-1Mo-1V TITANIUM ALLOY DIFFUSION WELD - FROM 2.0-INCH DIAMETER TUBULAR JOINT



22X 2A223240

1800°F - 90 Minutes - 100 PSI

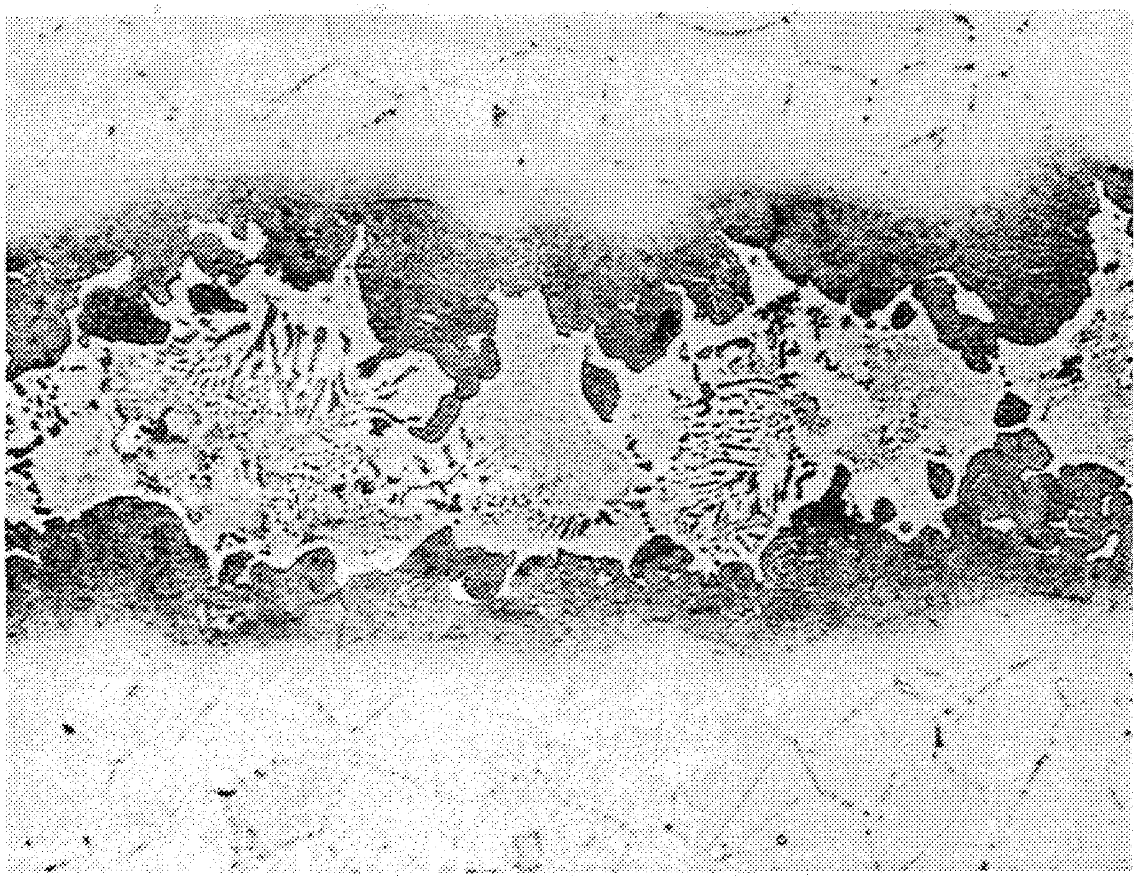
FIGURE 33 PHOTOMACROGRAPH OF A TITANIUM ALLOY LAMINATION JOINED BY DIFFUSION WELDING (Ti-8Al-1Mo-1V to Ti-5Al-2.5Sn)



100X 2A253176

500X 2A253177

FIGURE 34 PHOTOGRAPHS OF LAMINATED BERYLLIUM FOIL USING ALUMINUM FOIL FOR AN INTERLEAF (Roll Welded at 1000°F)



650X

2A253179

FIGURE 35 PHOTOMICROGRAPH OF INCONEL 600 JOINED BY DIFFUSION WELDING USING GOLD FOIL

REFERENCES

1. Crane, C.H.; Lovell, D.T.; Baginski, W.A.; "Research Study for Development of Techniques for Joining of Dissimilar Metal", The Boeing Company, Seattle, Washington, for NASA-Huntsville, Alabama, Contract NAS8-11307, Final Report, September 1965.

2. Crane, C.H.; Torgerson, R.T.; Lovell, D.T.; Baginski, W.A.; "Study of Dissimilar Metal Joining by Solid State Welding", The Boeing Company, Seattle, Washington, for NASA-Huntsville, Alabama, Contract NAS8-20156, Final Report, October 1966.

ACKNOWLEDGEMENT

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APPENDIX A

ELECTROPLATING PROCEDURES FOR AISI TYPE 321 STAINLESS STEEL, 2219 ALUMINUM ALLOY AND TITANIUM ALLOYS

APPENDIX A

1. Procedure for Silver Plating AISI Type 321 Stainless Steel

   a. Vapor degrease.

   b. Cathodic clean in alkaline electrocleaner.

   c. Anodic clean in 60% H_2SO_4 - 45 seconds.

   d. Strike in all chloride nickel strike - 30 seconds.

   e. Copper strike in conventional Rochelle salt copper cyanide plating solution.

   f. Silver plate .0005/.0007" thick in Lea-Ronal proprietary silver plating solution.

2. Procedure for Silver Plating 2219 Aluminum Alloy

   a. Vapor degrease.

   b. Soak clean in non-silicated aluminum cleaner.

   c. Deoxidize at room temperature.

   d. Dip in nitric-hydrofluoric acid-5 seconds.

   e. Zincate (conventional zinc immersion bath).

   f. Remove zinc by dipping in concentrated nitric-acid.

   g. Repeat step e.

   h. Copper strike .00002" thick in conventional Rochelle salt copper cyanide plating solution with 10.0 to 10.5 pH.

   i. Silver plate .0005/.0007" thick in Lea-Ronal proprietary silver plating solution.

3. Procedure for Plating Ti-5Al-2.5Sn and Ti-8Al-1Mo-1V Titanium Alloys

   a. Solvent clean.

   b. Alkaline clean.

   c. Etch in nitric-hydrofluoric acid solution.

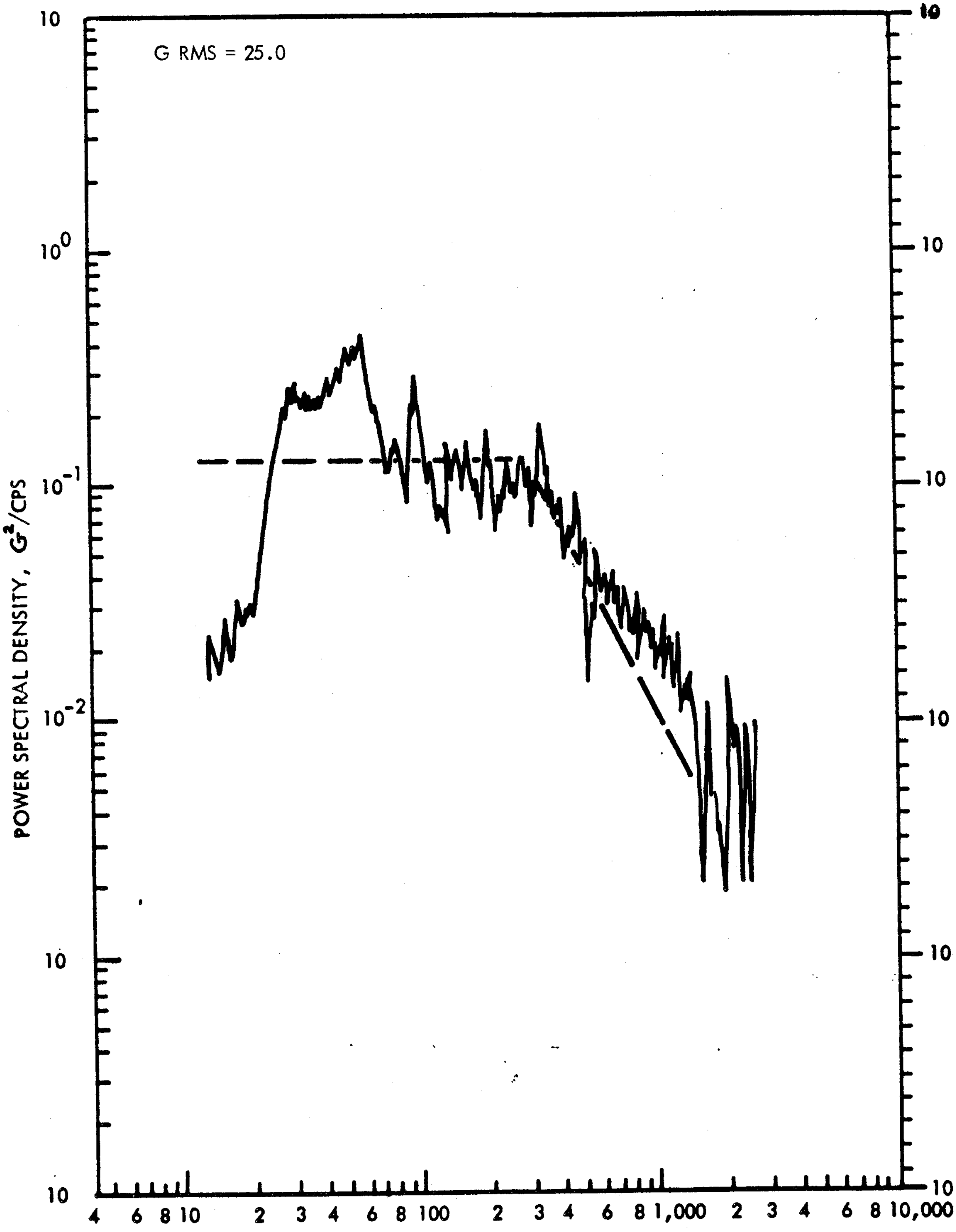
   d. Anodize in a solution of 7 parts by volume acetic acid and one part hydrofluoric acid (70%) and at a current density of 3 ASF.

   e. Silver strike using conventional silver strike bath.

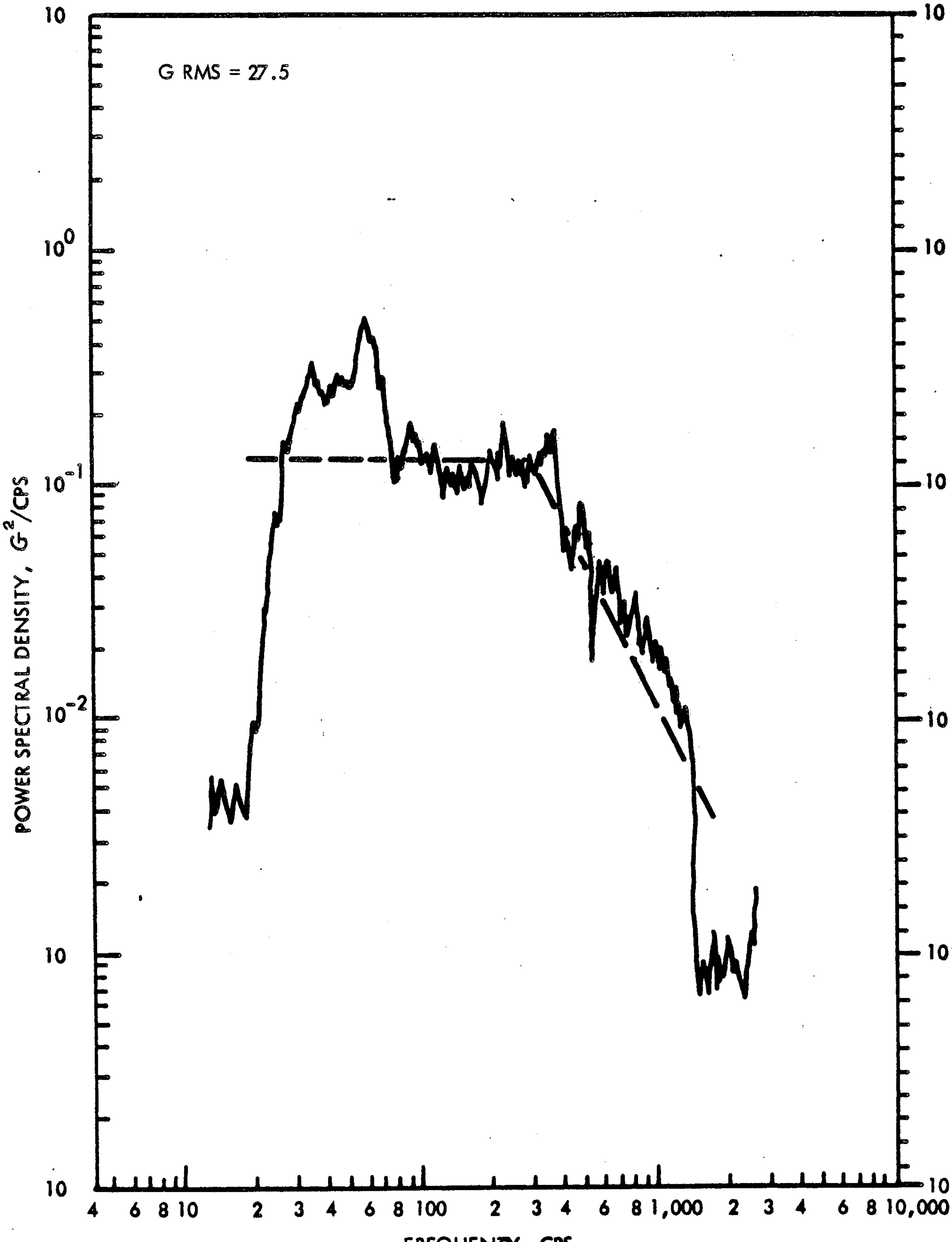
   f. Silver plate .0005/.0007" thick using conventional silver cyanide bath at room temperature and with a current density of 10 ASF.

APPENDIX B

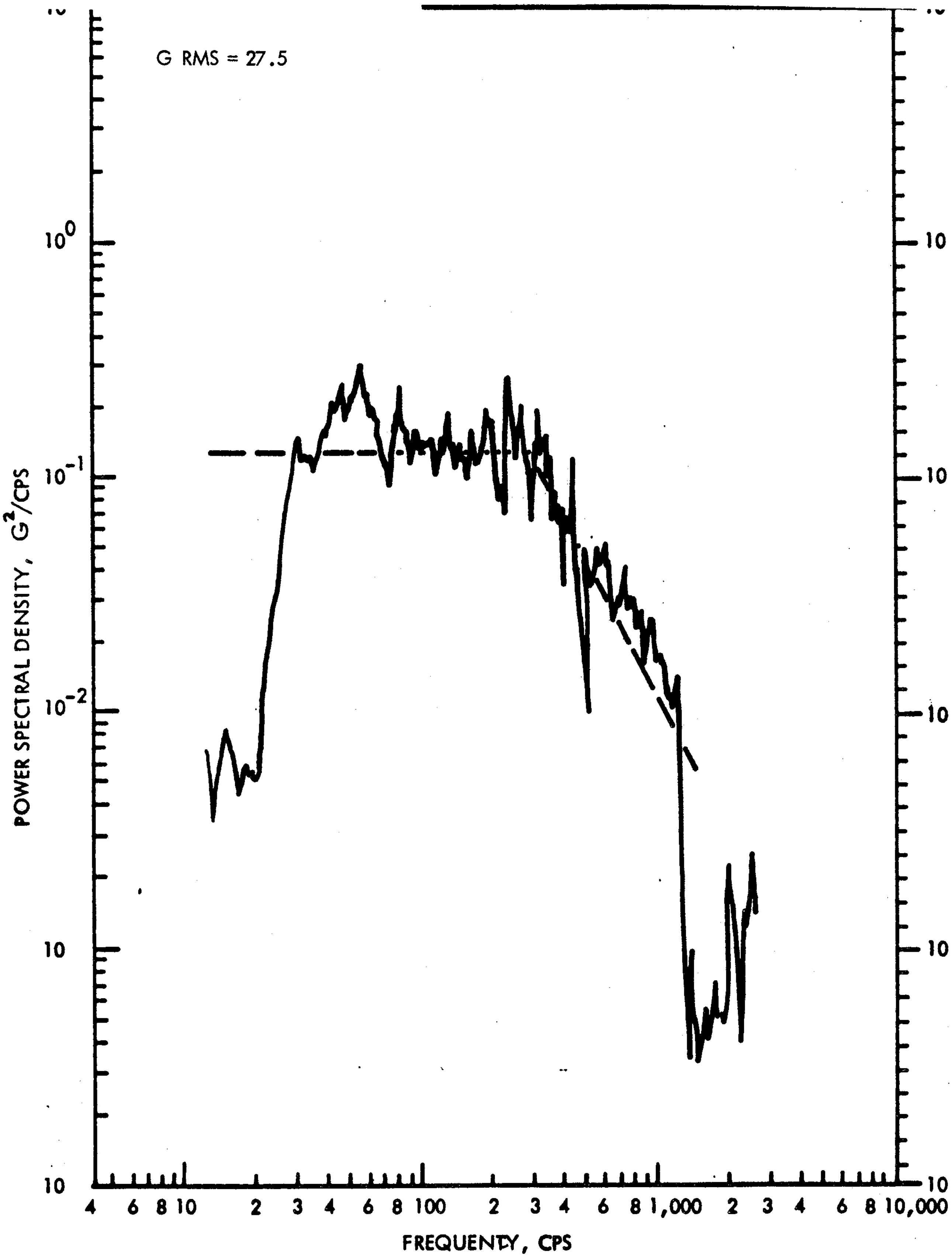
POWER SPECTRAL DENSITY CURVES



POWER SPECTRAL DENSITY VERSUS FREQUENCY
SPECIMEN A6



POWER SPECTRAL DENSITY VERSUS FREQUENCY
SPECIMEN A8



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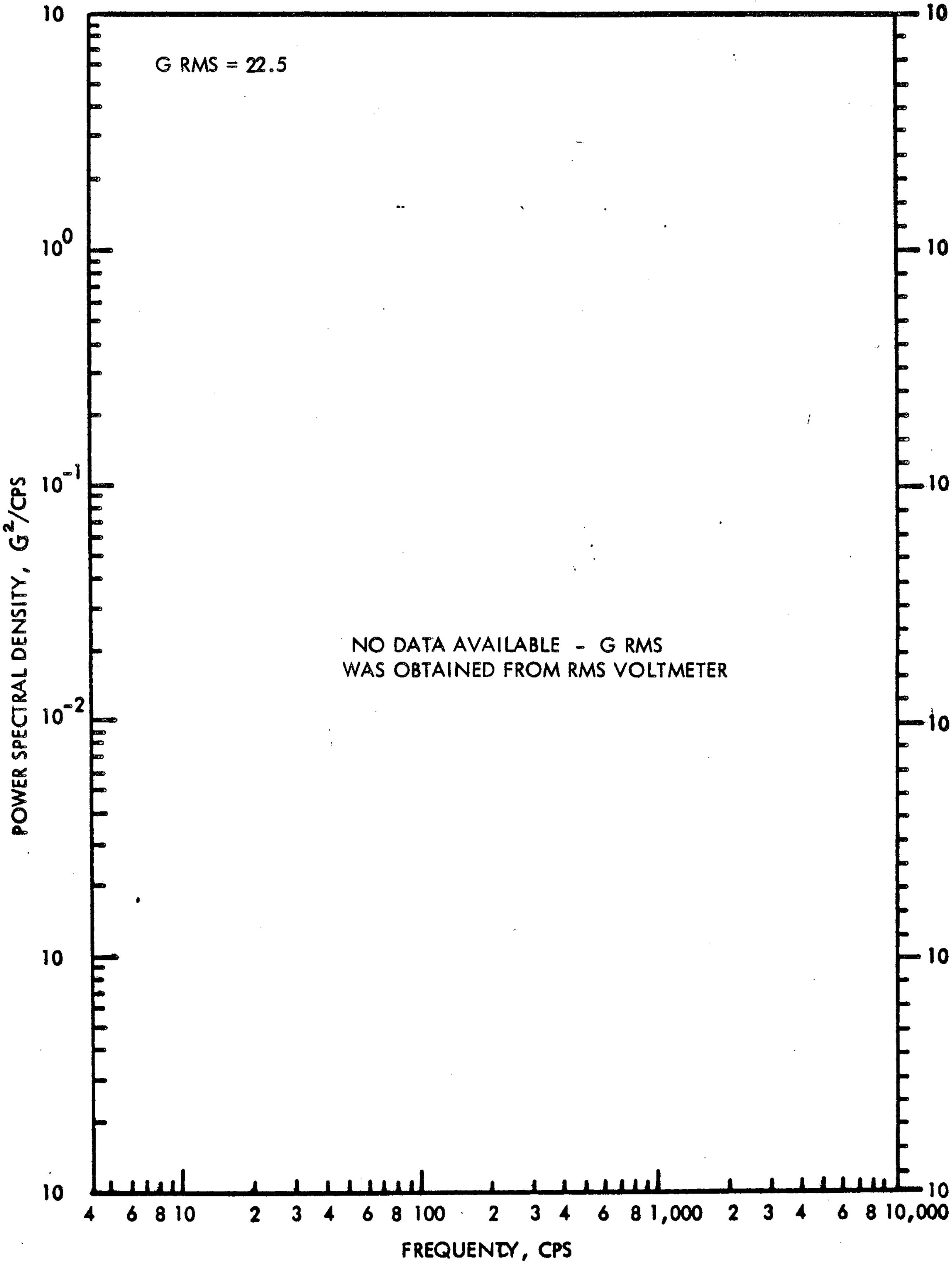
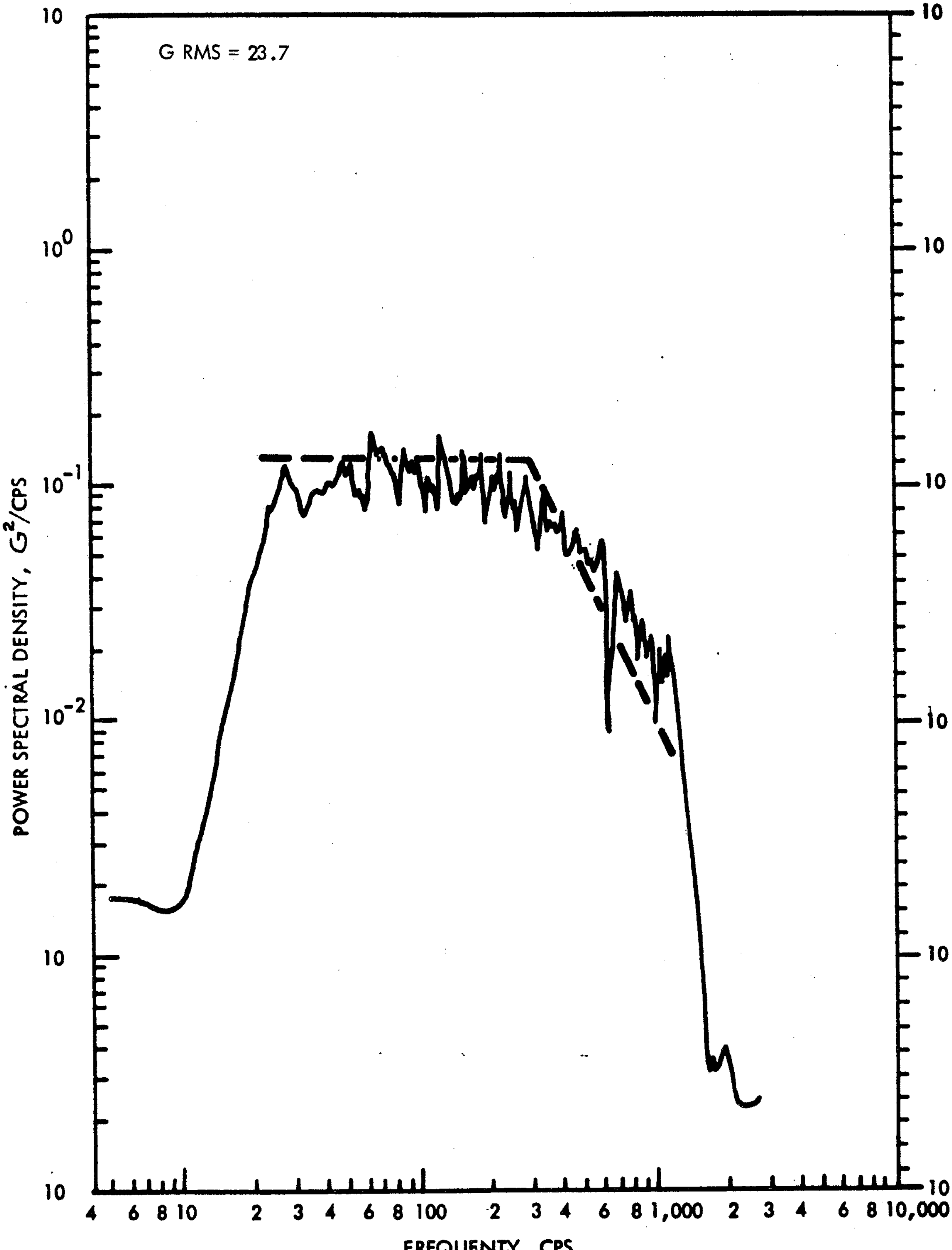
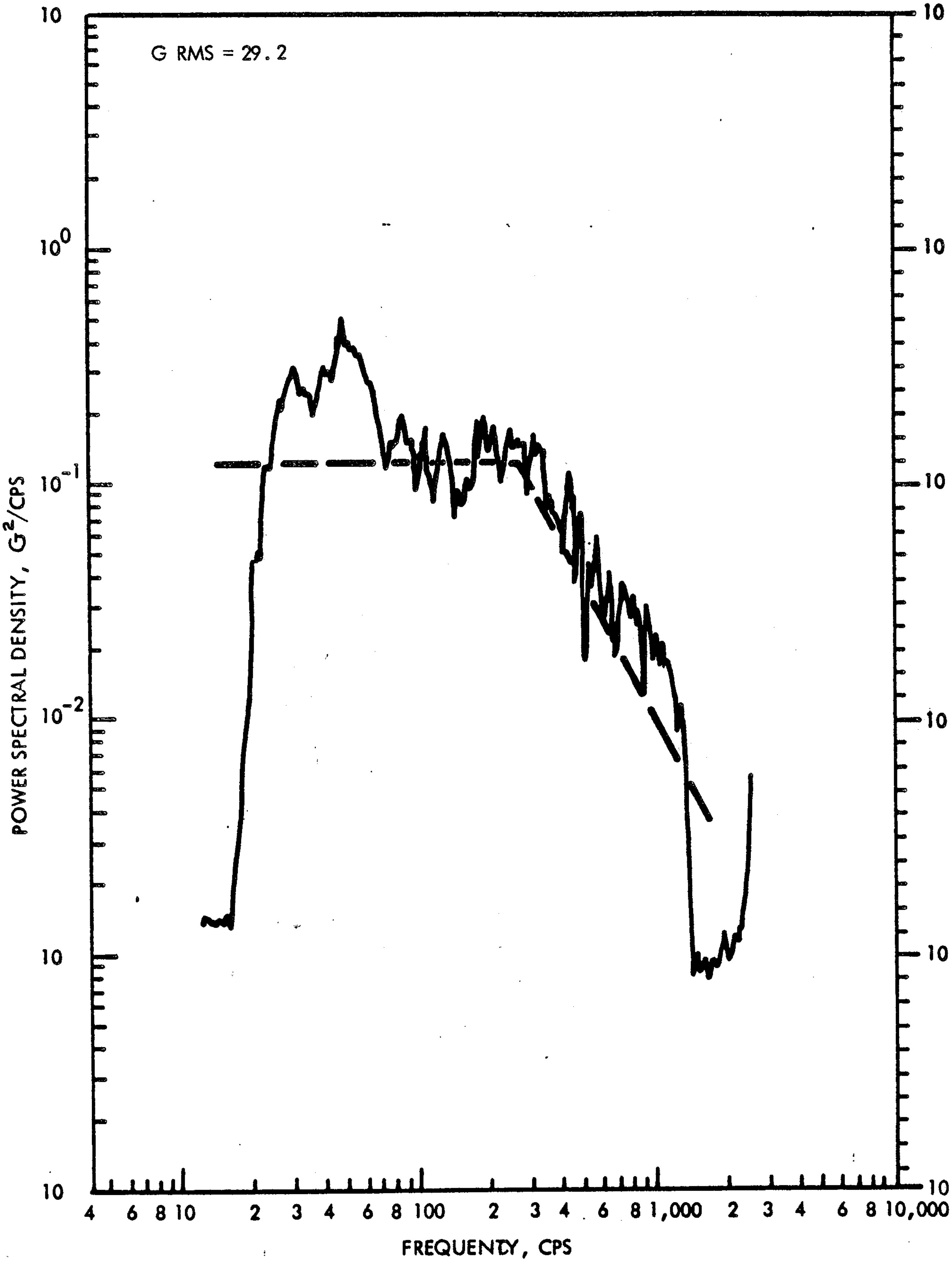
SPECIMEN A9



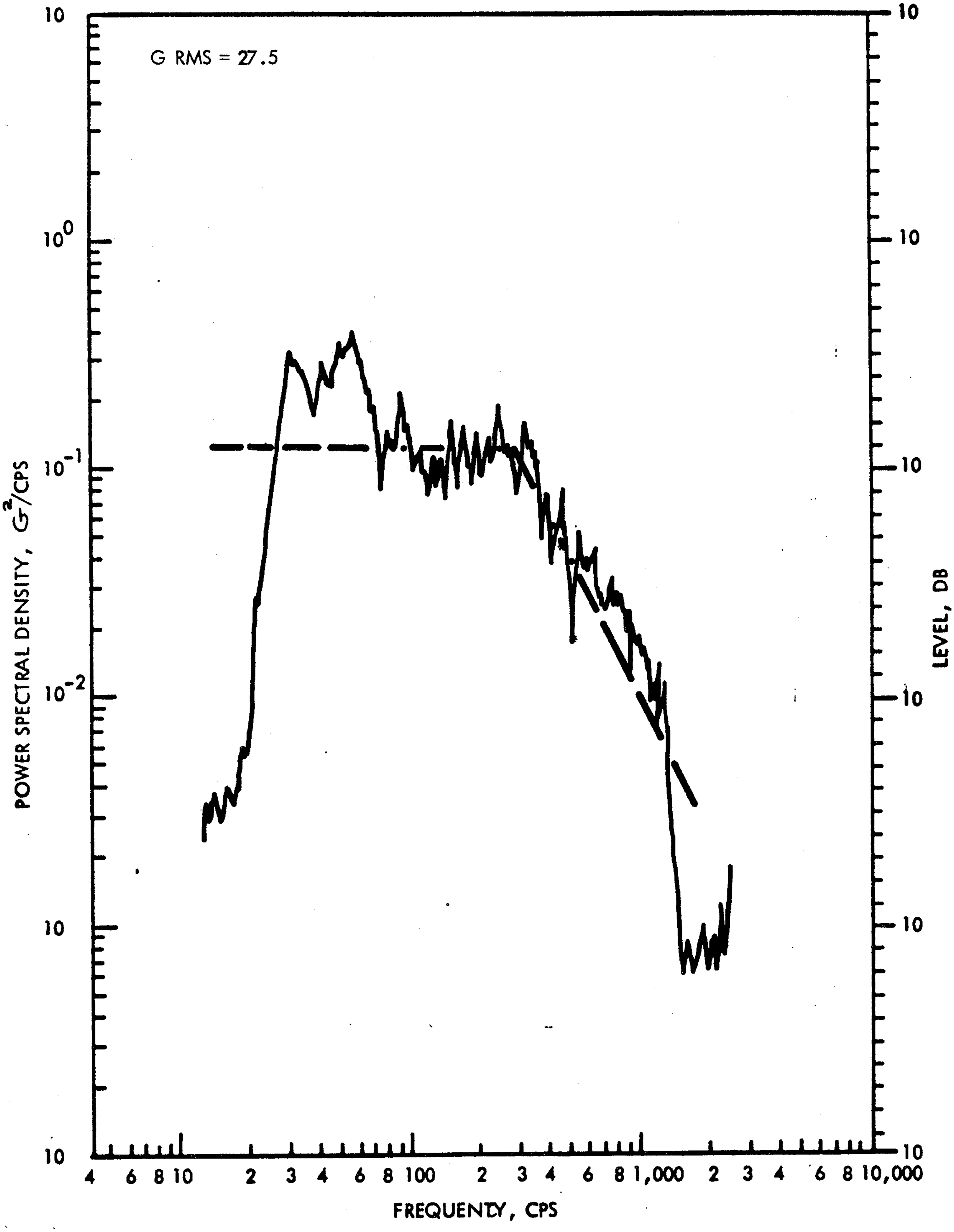
POWER SPECTRAL DENSITY VERSUS FREQUENCY
SPECIMEN A19



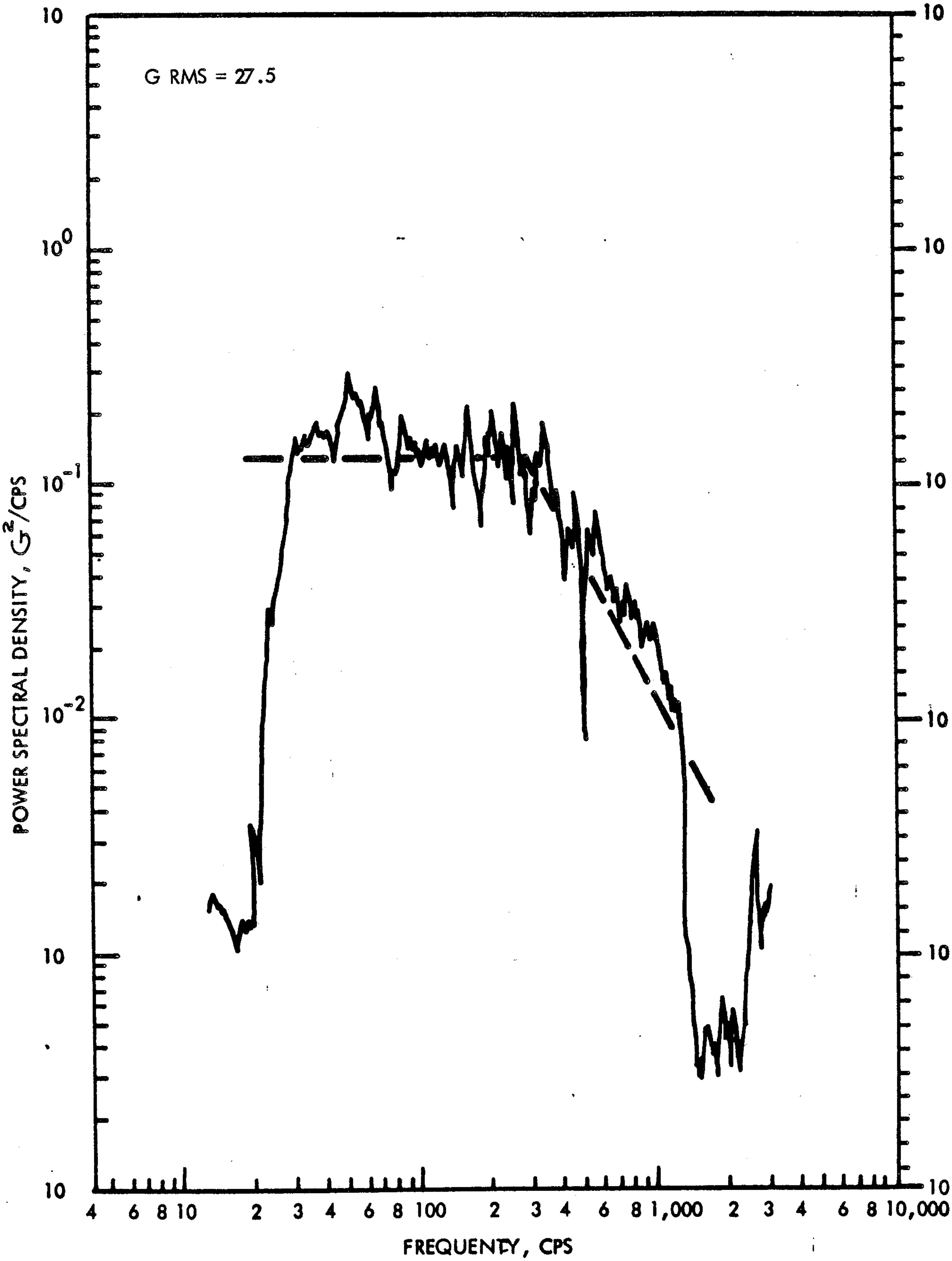
POWER SPECTRAL DENSITY VERSUS FREQUENCY
SPECIMEN A20



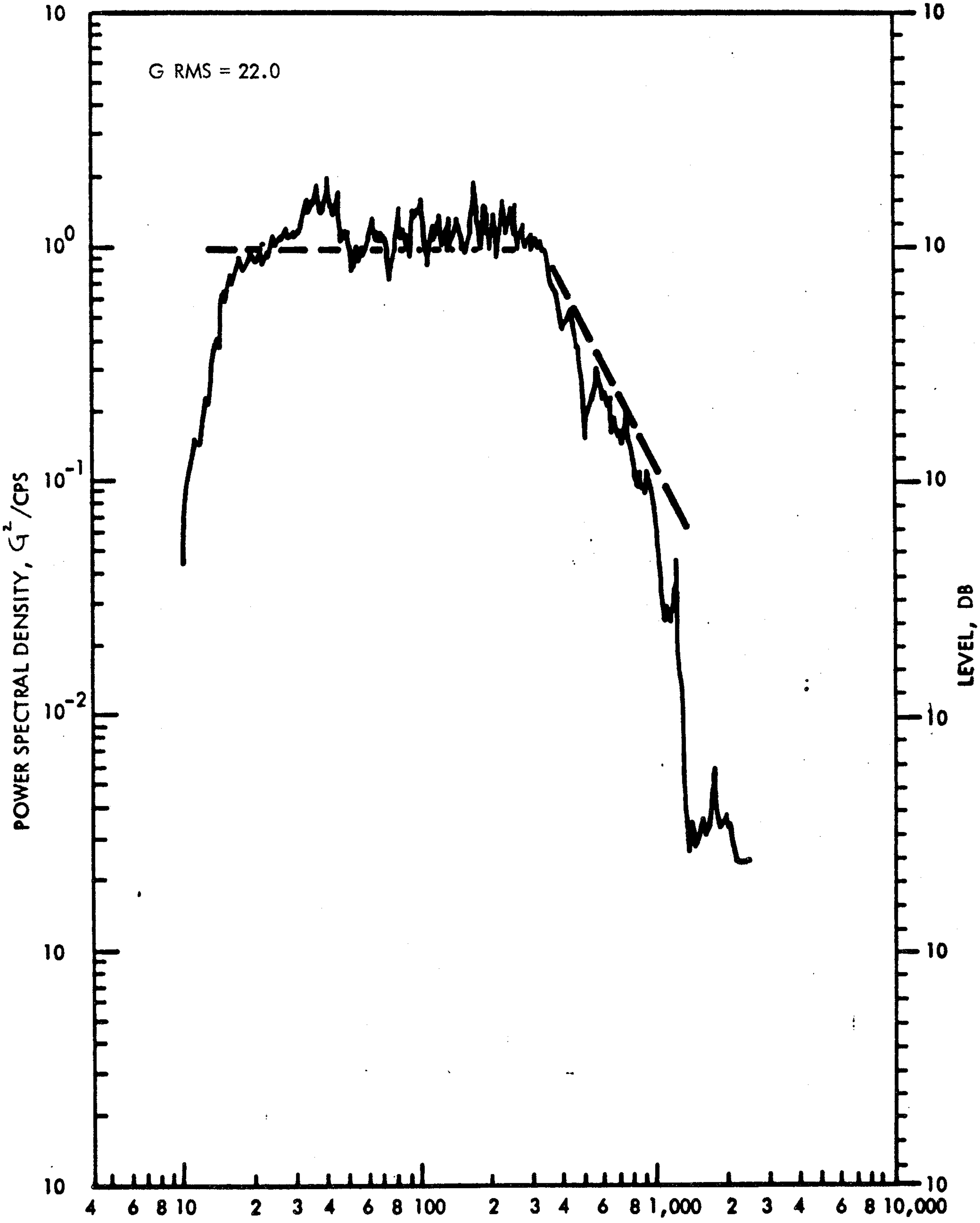
POWER SPECTRAL DENSITY VERSUS FREQUENCY
SPECIMEN B6



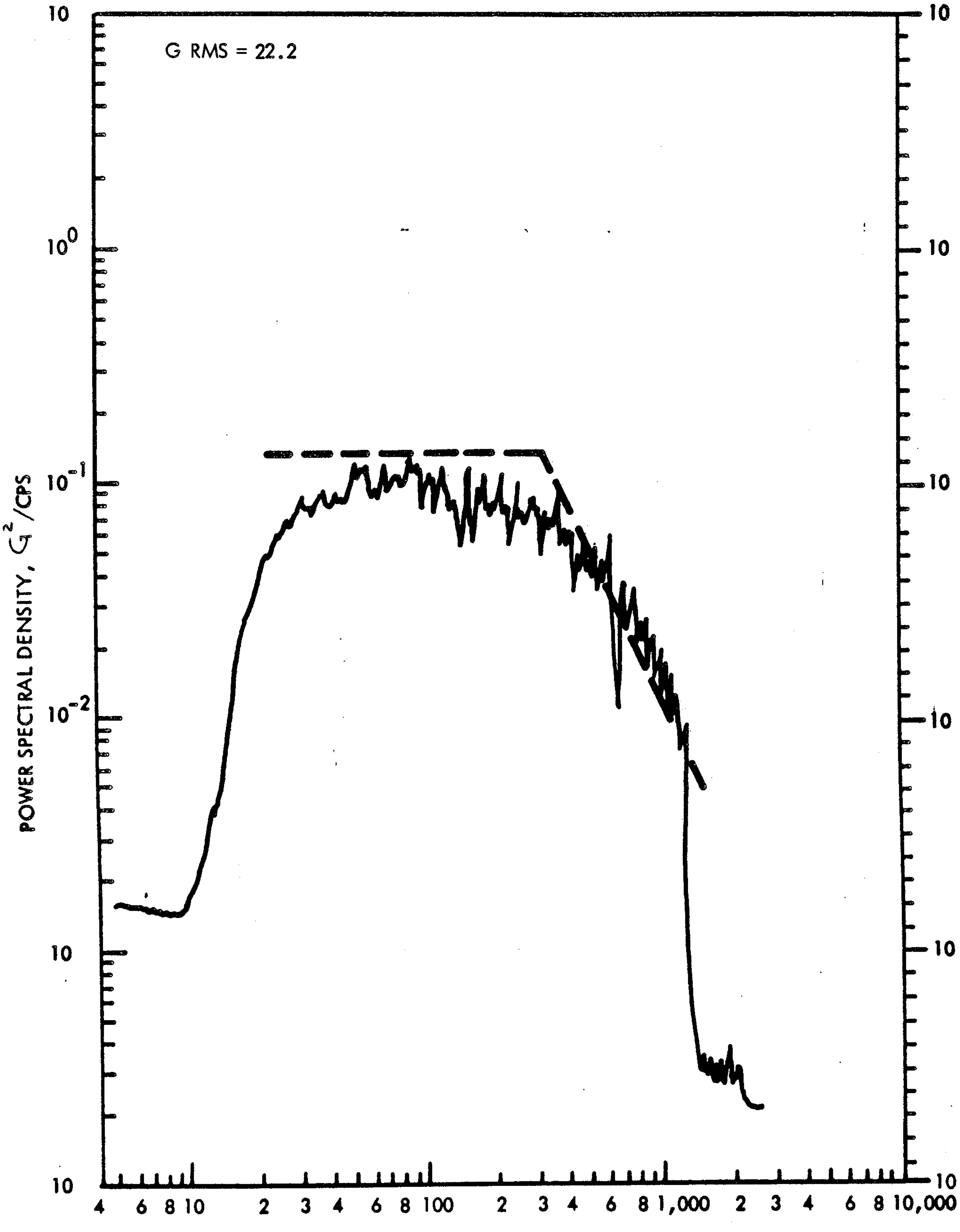
POWER SPECTRAL DENSITY VERSUS FREQUENCY
SPECIMEN B7



POWER SPECTRAL DENSITY VERSUS FREQUENCY
SPECIMEN B8



POWER SPECTRAL DENSITY VERSUS FREQUENCY
SPECIMEN B19



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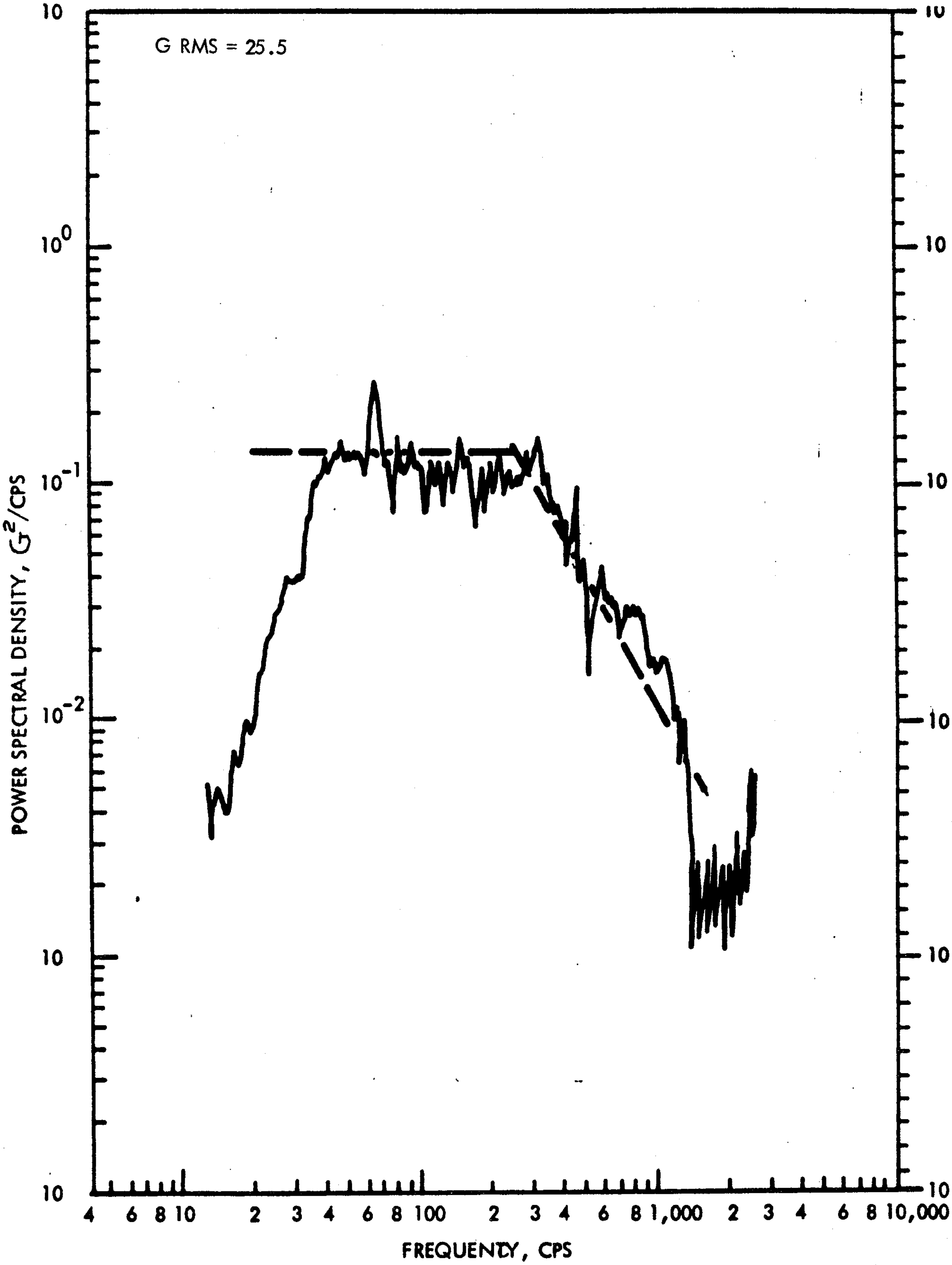
SPECIMEN B20



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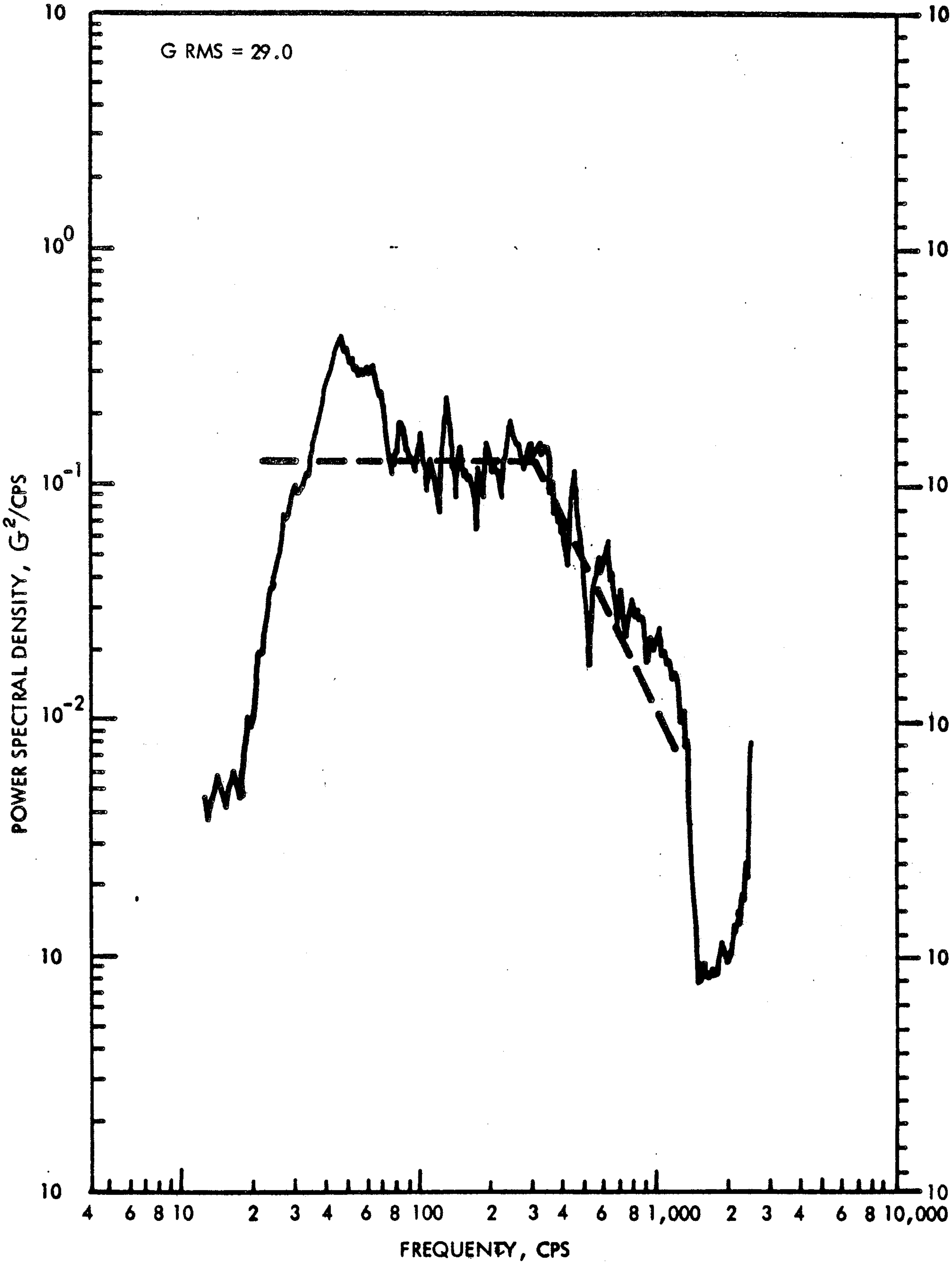
SPECIMEN C6



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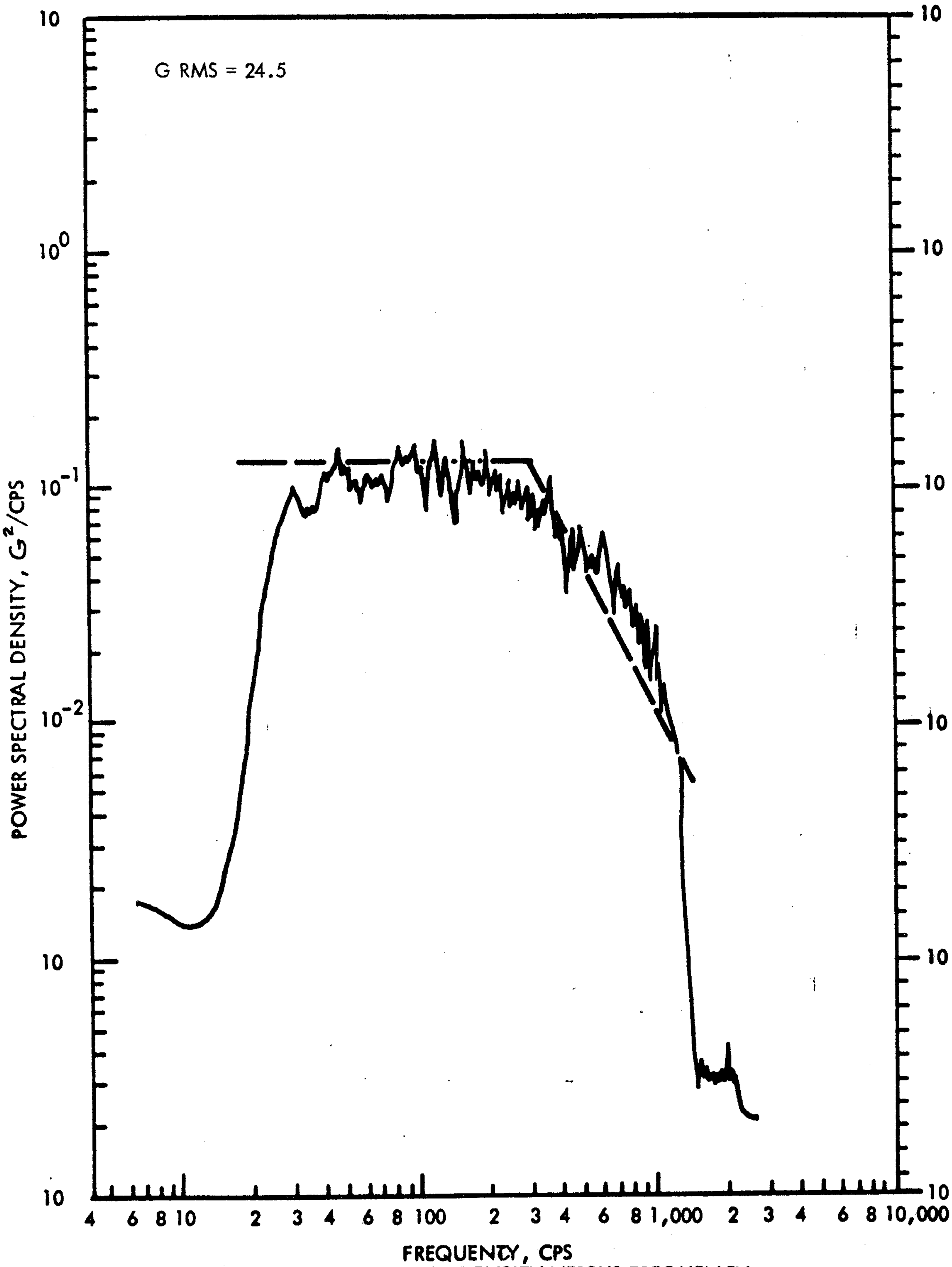

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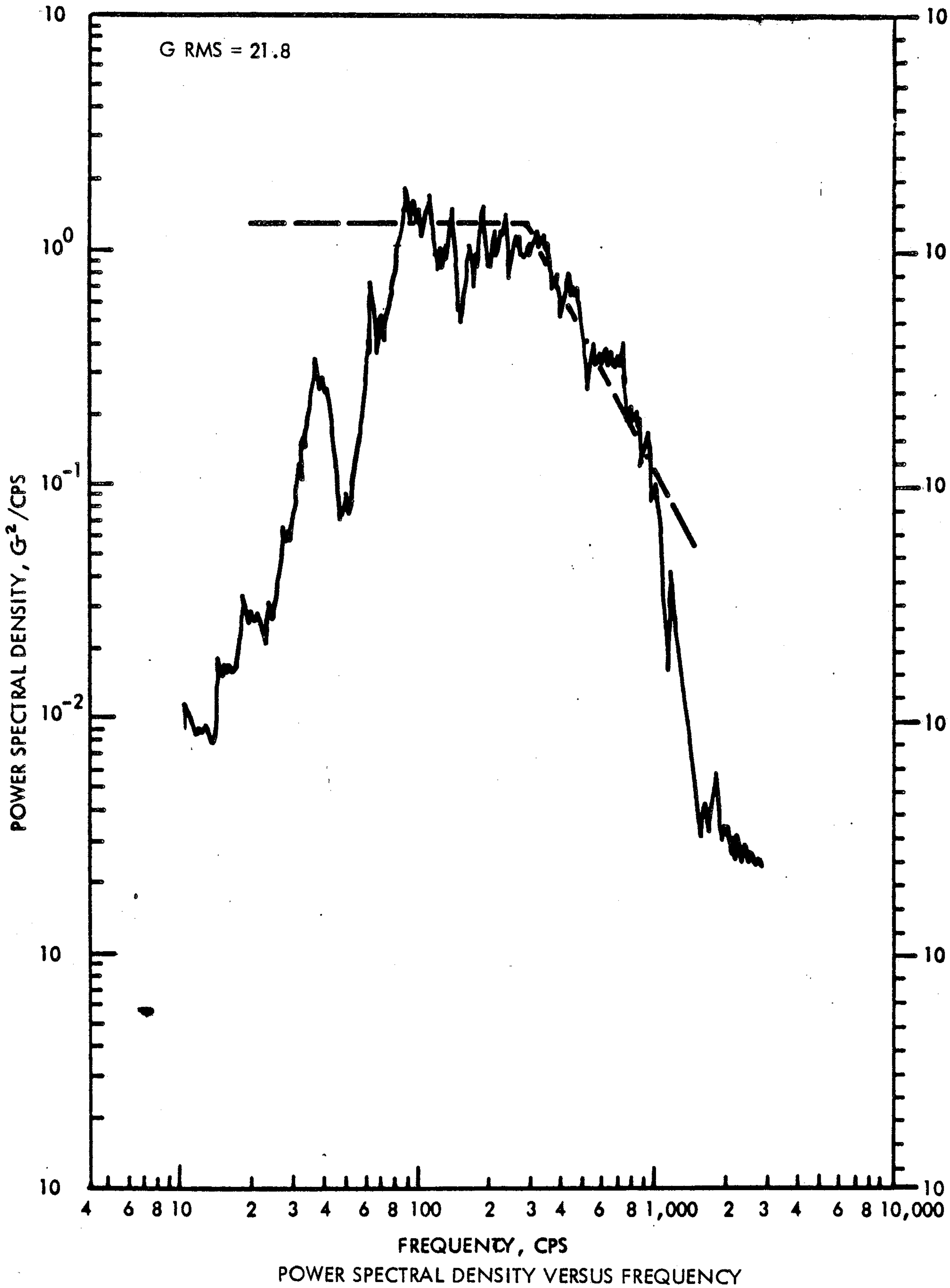
SPECIMEN C19



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